

KALDERA

A high-average power LPA drive laser

EAAC
Sept 22nd, 2025

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The DESY Plasma Group

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Beam-Driven
Plasma
Acceleration

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Lutz
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Scientific
Engineering

Andi
Coordinator
Scientific
Infrastructure

Kaja
Scientific
Project
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Plasma R&D at DESY

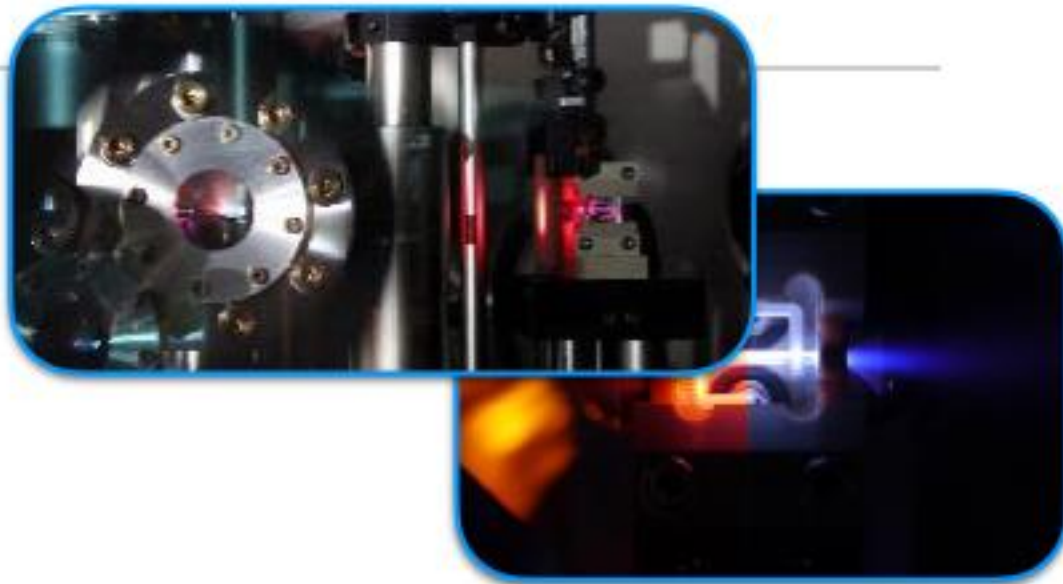
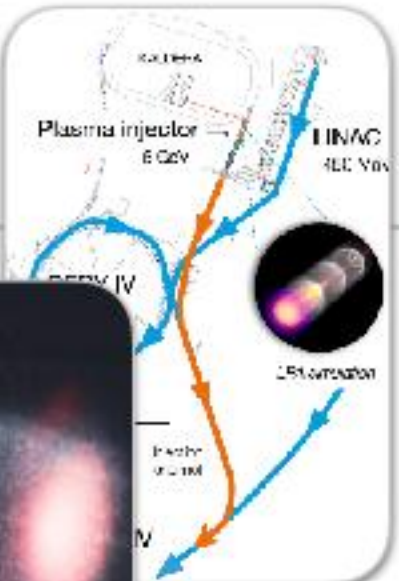
Our portfolio at plasma.desy.de

Scientific
Engineering



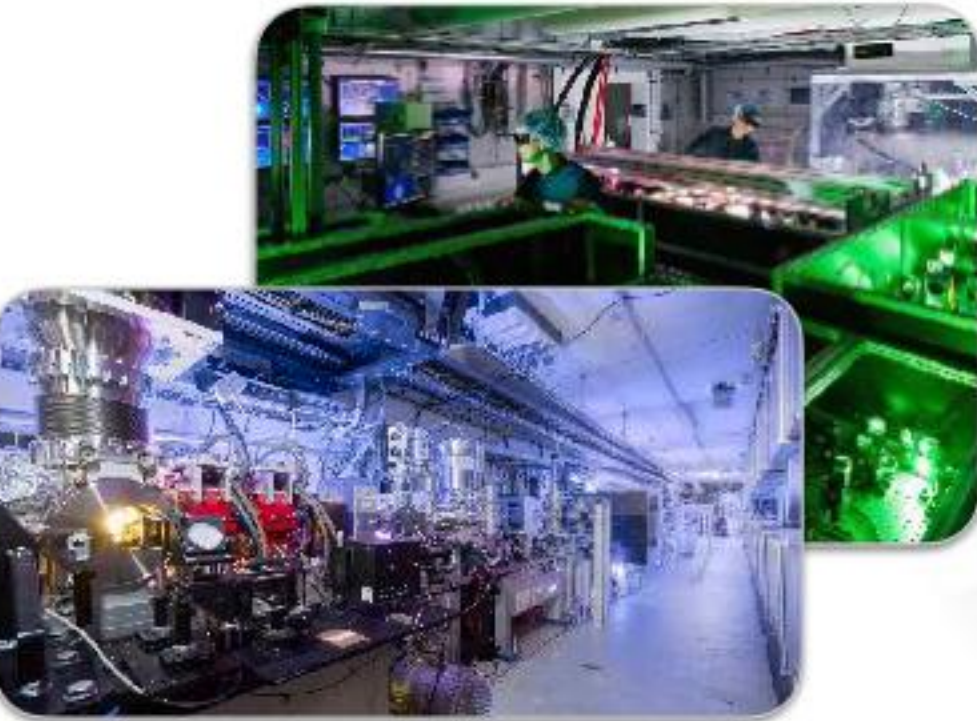
PETRA

Theory &
Simulations



LPA Applications

- RF accelerators
- plasma accelerators



LUX Laser-Plasma
Accelerator



KALDERA
High Rep-Rate LPA



FLASHForward
Beam-Driven Plasma Acc.

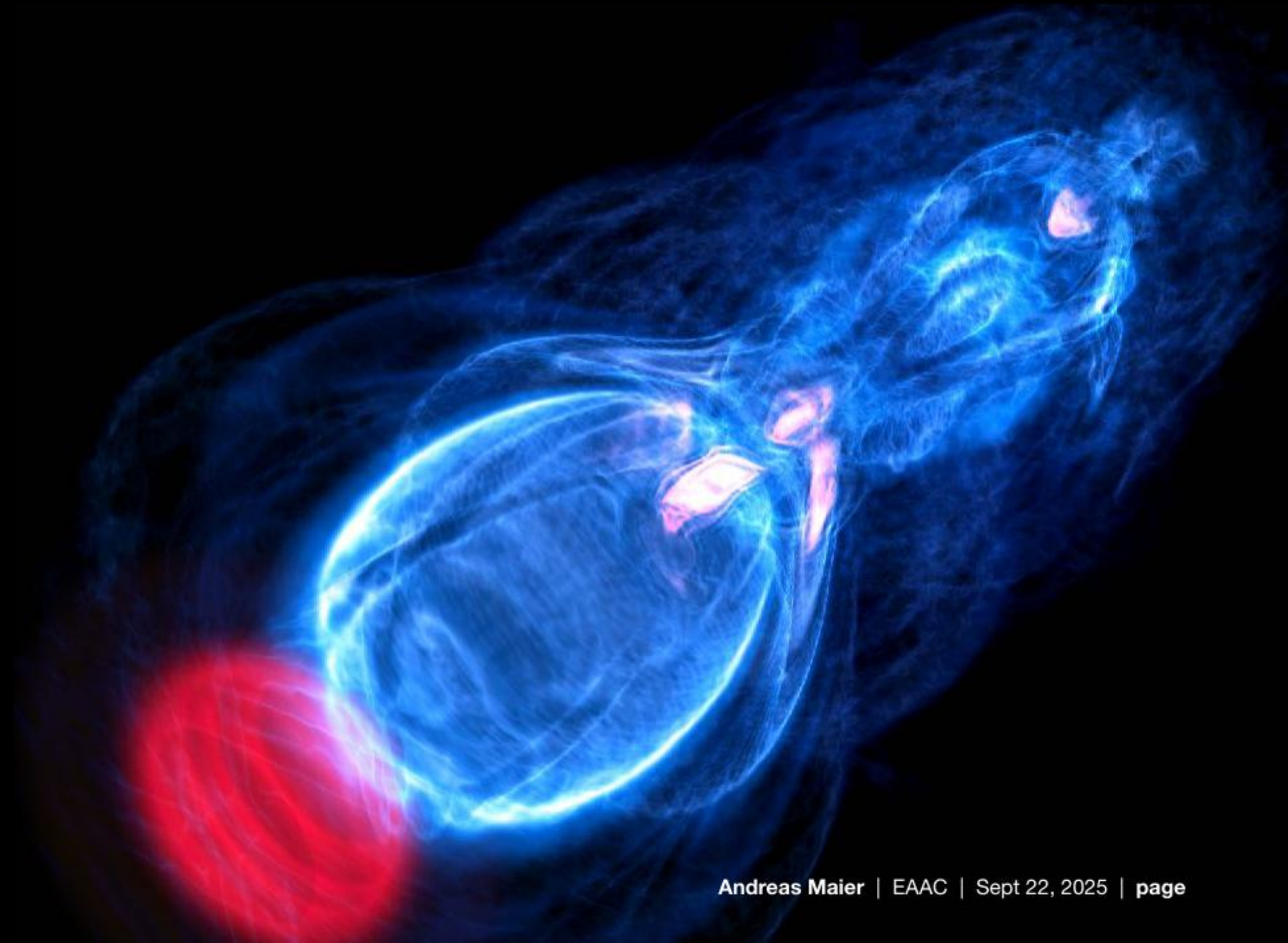


Laser-Plasma Acceleration

Details matter

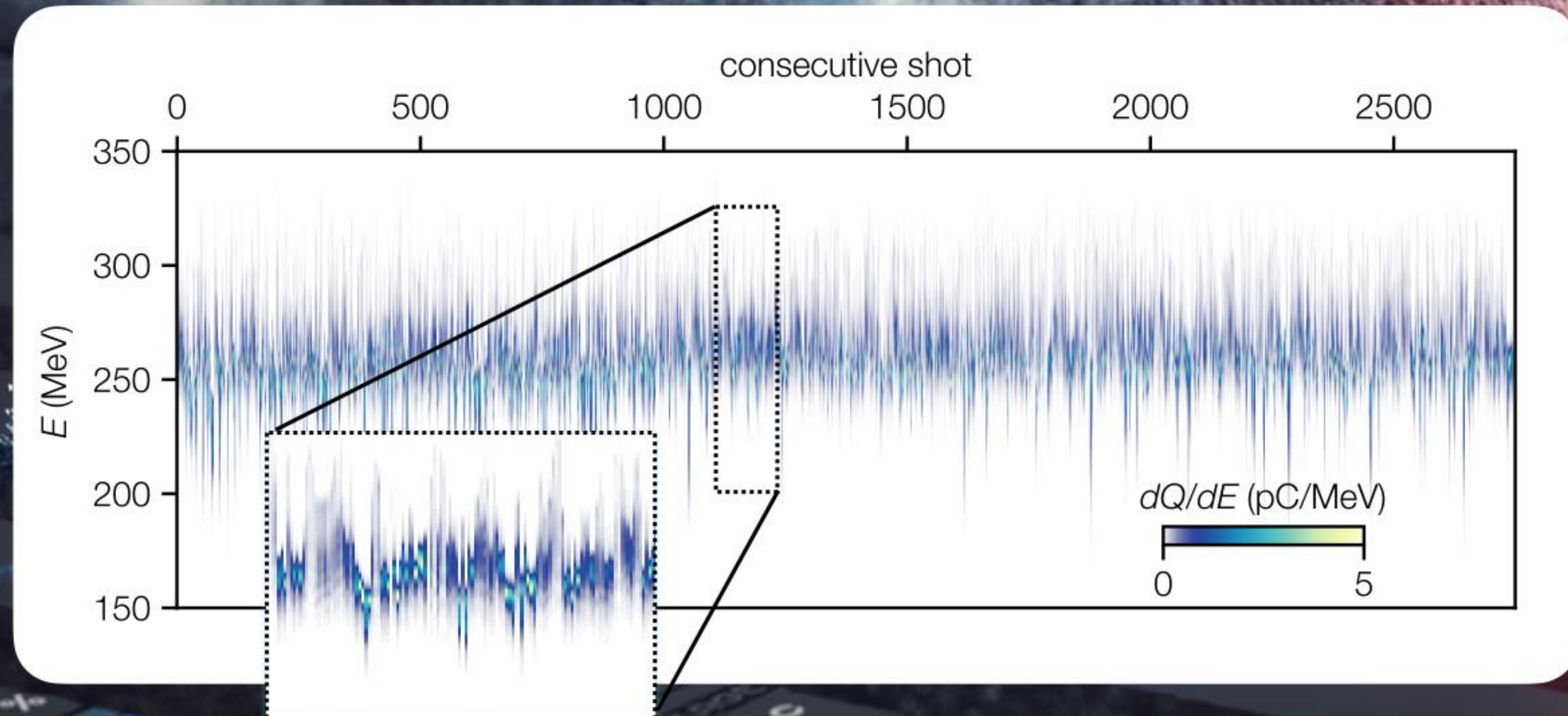
A new accelerator cavity
with every shot

Subtle variations in the
drive laser pulse effect the
electron beams.



Chasing quality on shaky ground

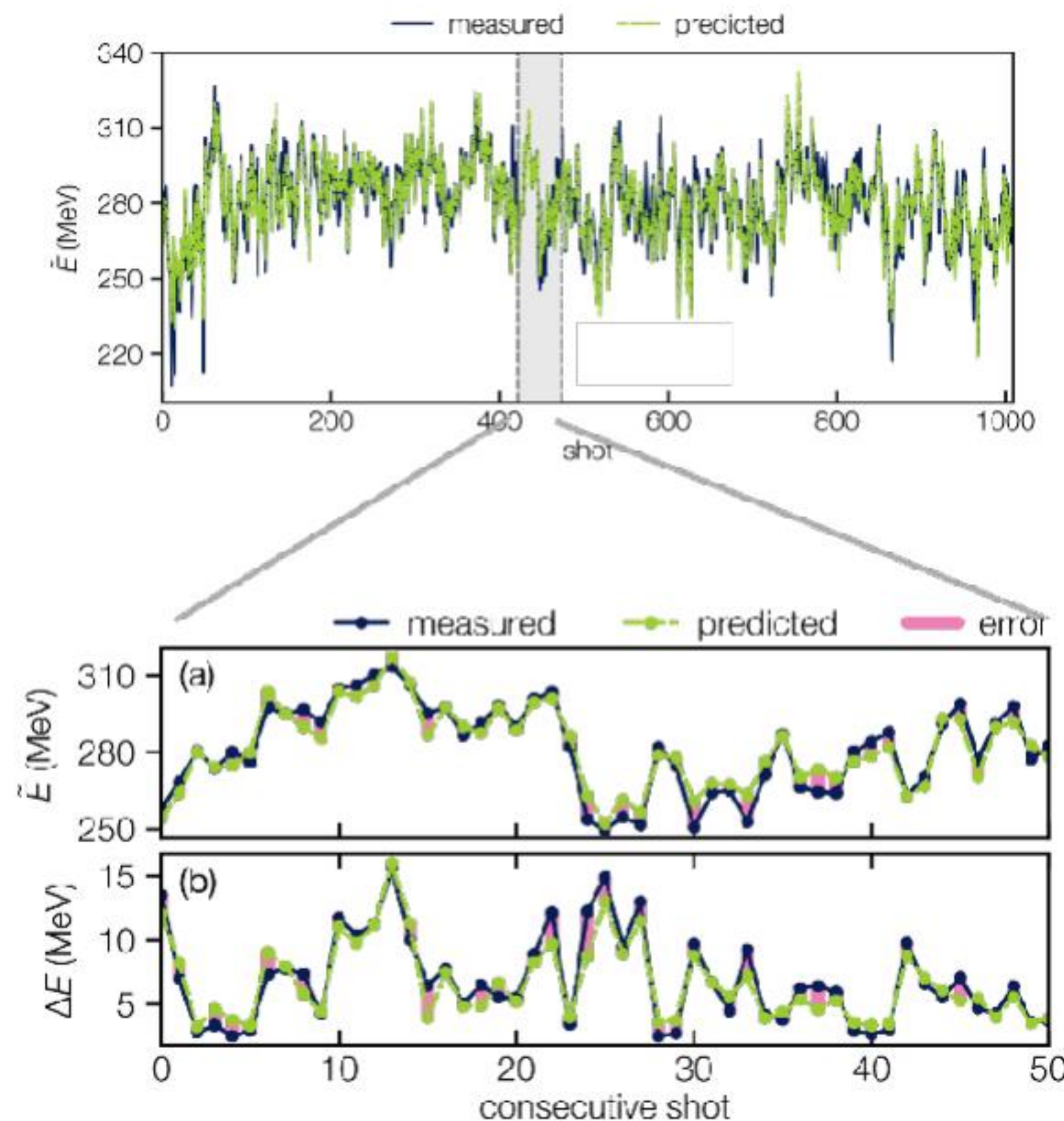
Percent-level jitter prevents further performance improvements



Experiments make the case for high rep rate

Active stabilization and feedback will enable high-quality LPA electron beams

M. Kirchen et al., Phys. Rev. Lett. 126, 174801 (2021)



- > We can correlate laser properties and electron beam properties on a single-shot basis
- > (Good news: Physics is still deterministic)
- > We have a recipe how to improve the electron beam performance:
 1. Optimize injected phase space, e.g., optimum beam loading, controlled injection, ...
 2. Deploy active stabilization and feedback to get the good beams more often

KALDERA: High Rep-Rate LPA at 100Hz and Above

Deploy active stabilization and feedback



Initiated by Wim

High rep-rate LPA

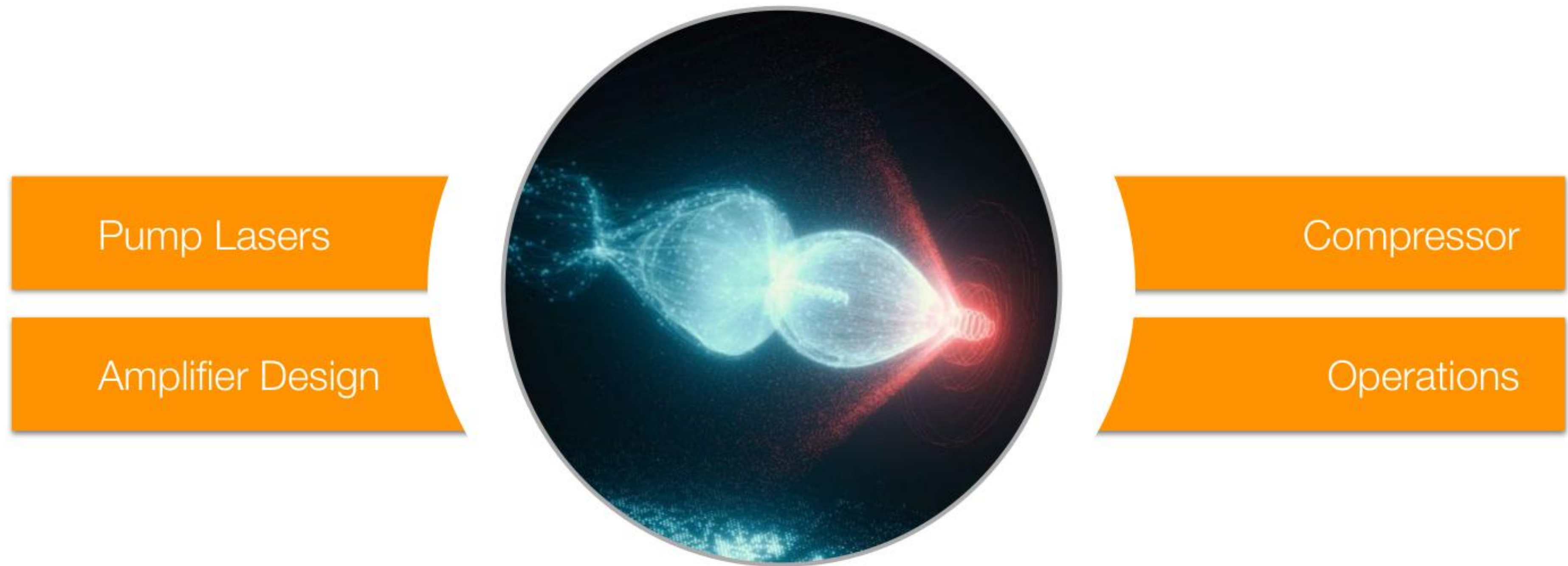
- > Active stabilization and feedback
- > Full control-system integration
- > Technology demonstrator

Goal

- > 100TW at up to 1kHz
- > High quality electron beams
- > Success is defined by LPA performance, not by laser performance

Some Challenges

Specifically for a Ti:Sa-based kW-class LPA drive laser

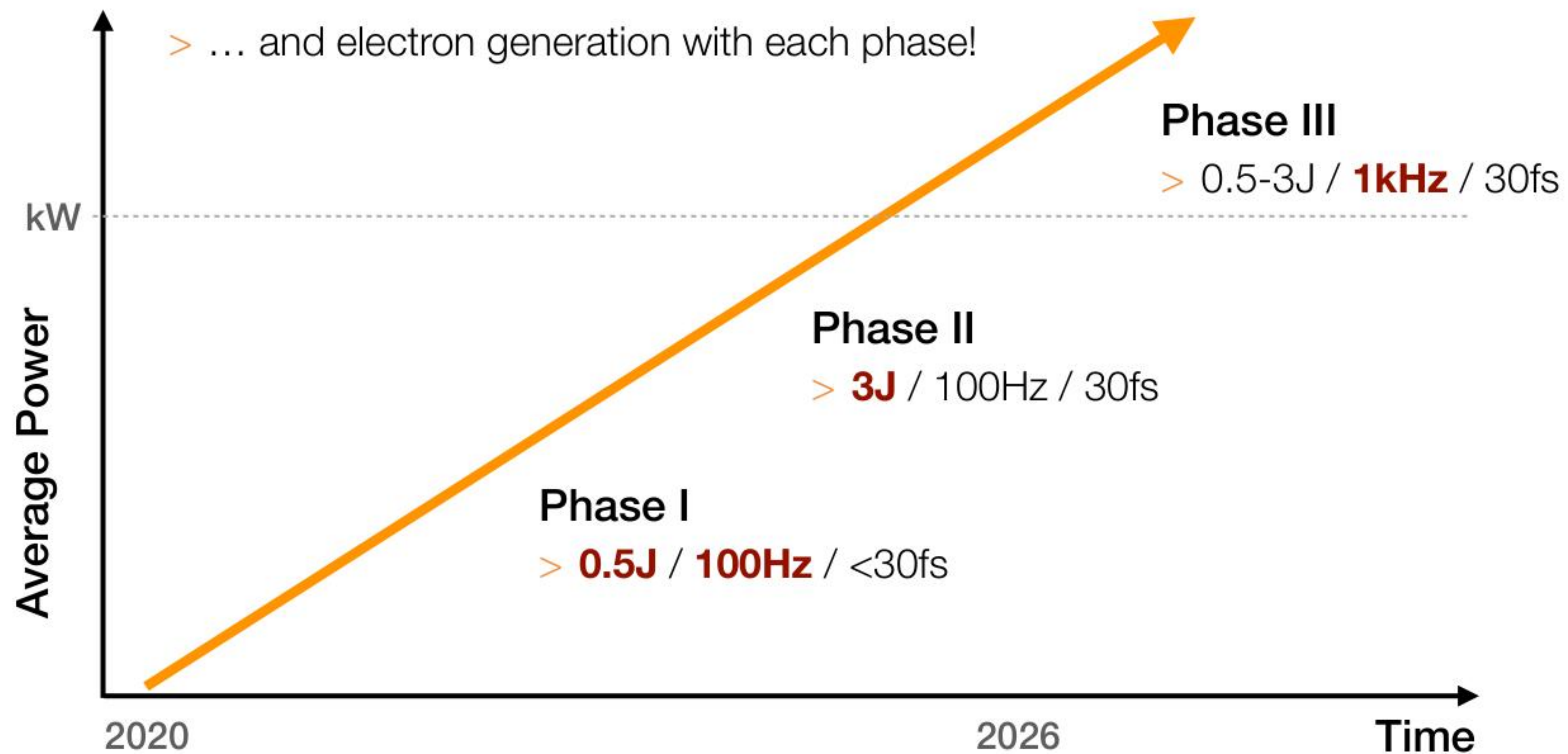


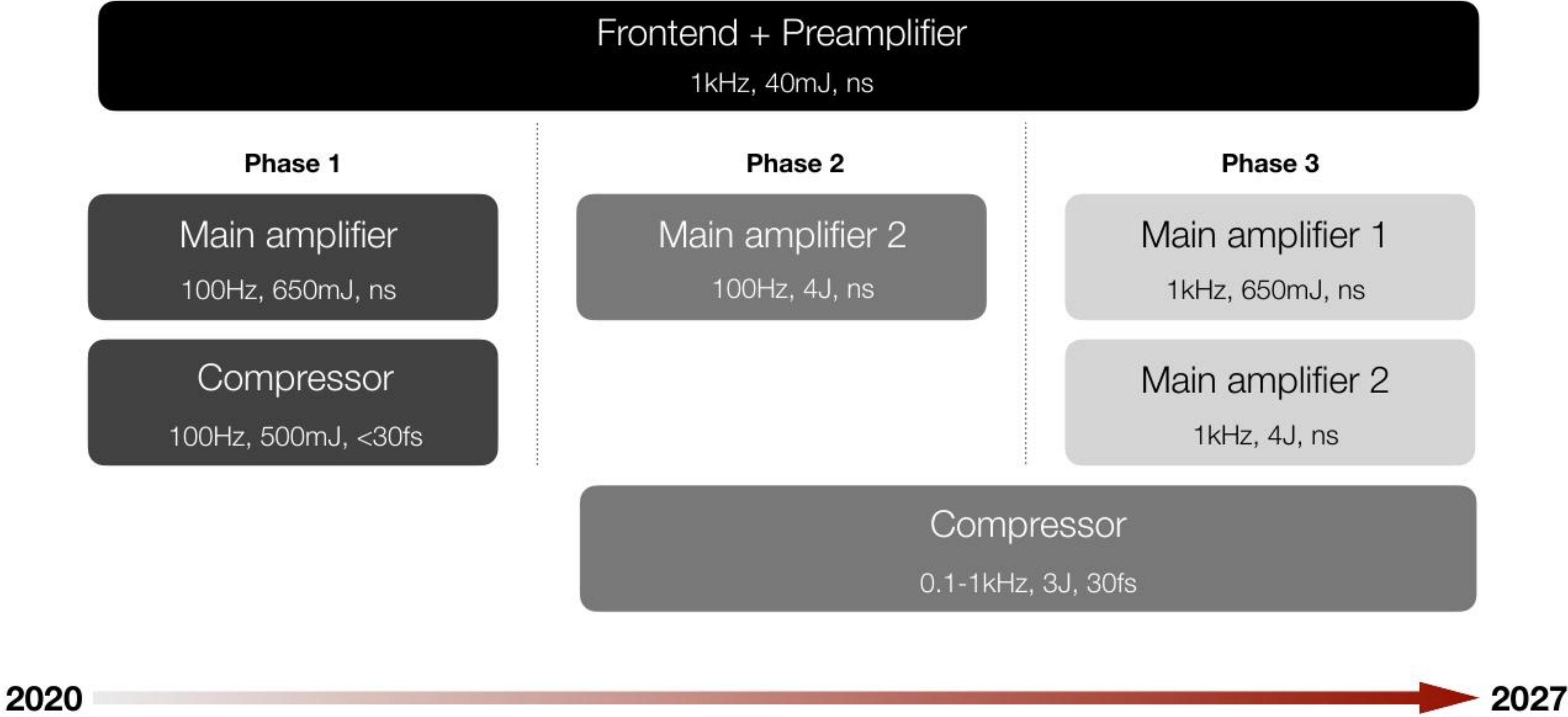
Laser Development

Roadmap



G. Palmer, L. Winkelmann, K. Schubert

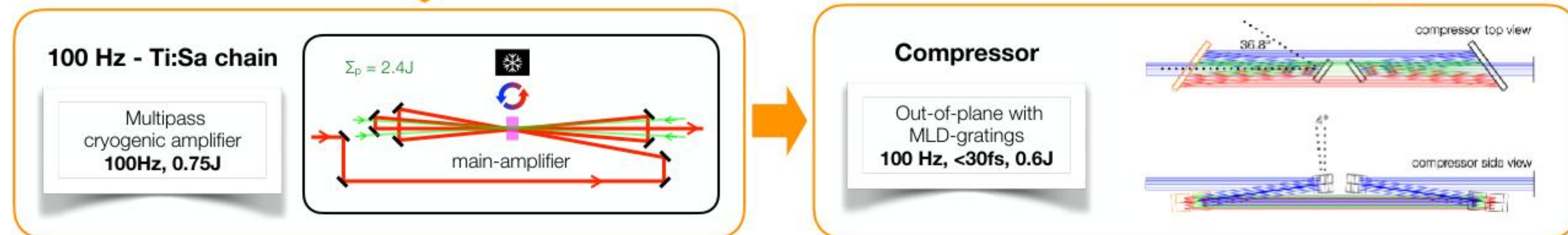
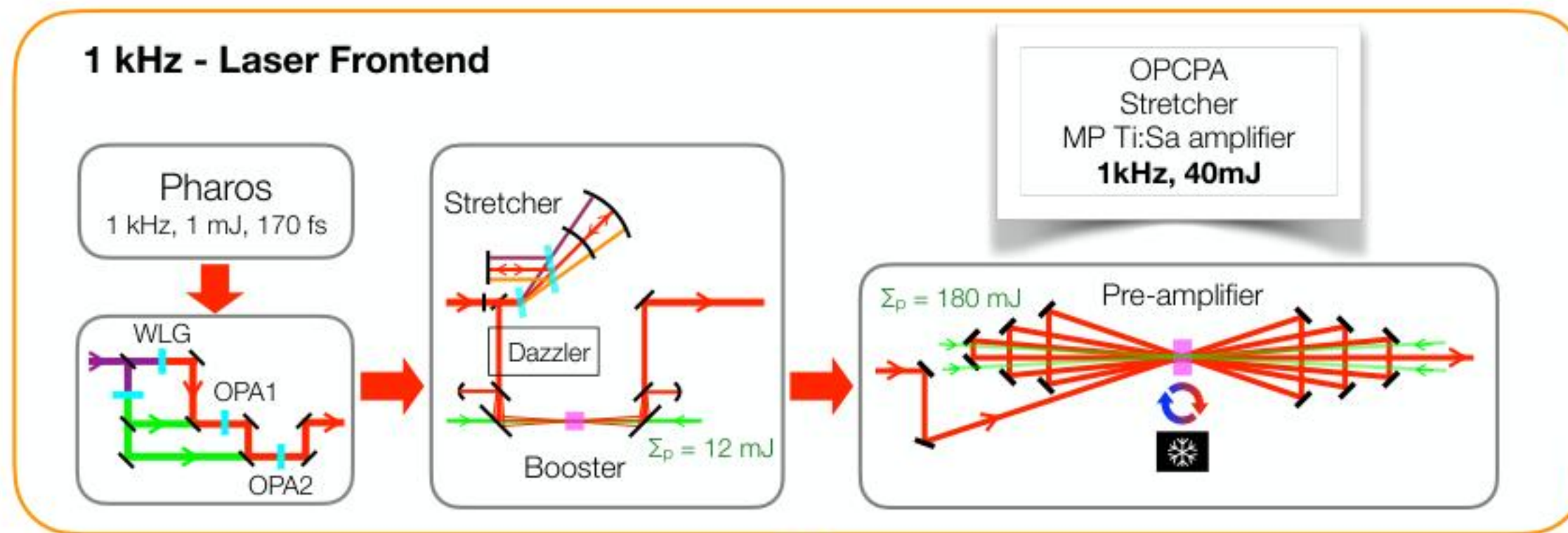




KALDERA

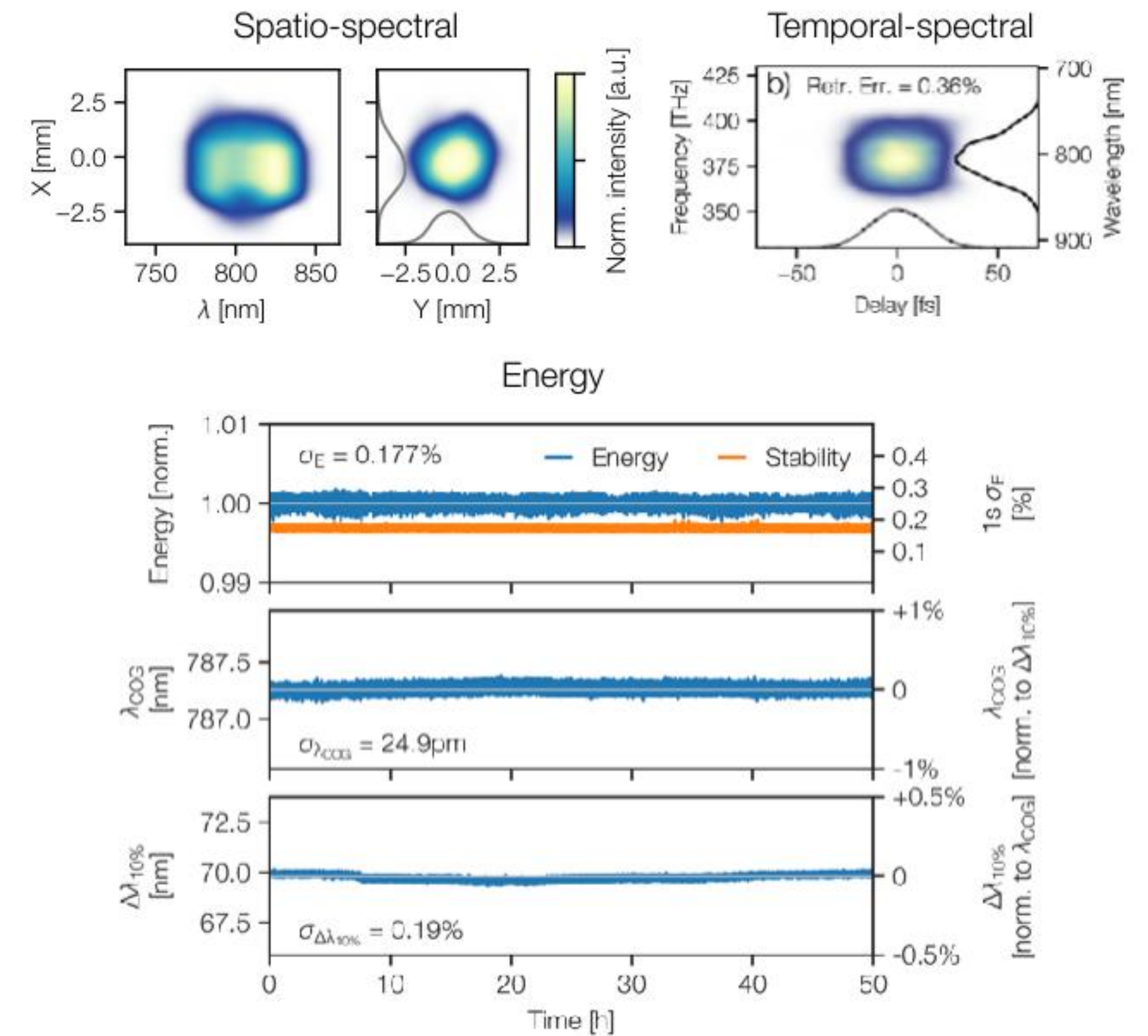
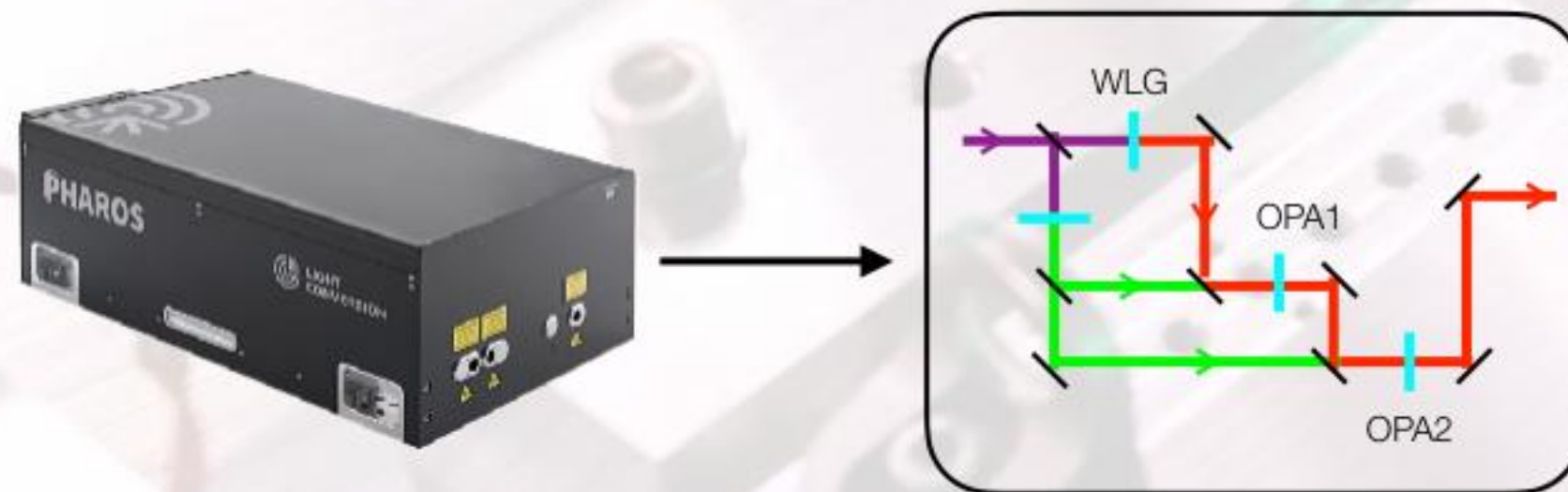
Phase 1: 0.5J on target at 100Hz

credit: G. Palmer & team



OPCPA seed „MASUBI“

- > Pharos drive/seed laser (Light Conversion)
- > White light seeded OPCPA
- > Up to $60\mu\text{J}$ @ kHz
- > 25fs bandwidth
- > 0.17% energy stability over 50hrs
- > Automated-tuning to reproducible working points
- > High contrast higher 10^{-10}



KALDERA

PreAmp (MERAPI)

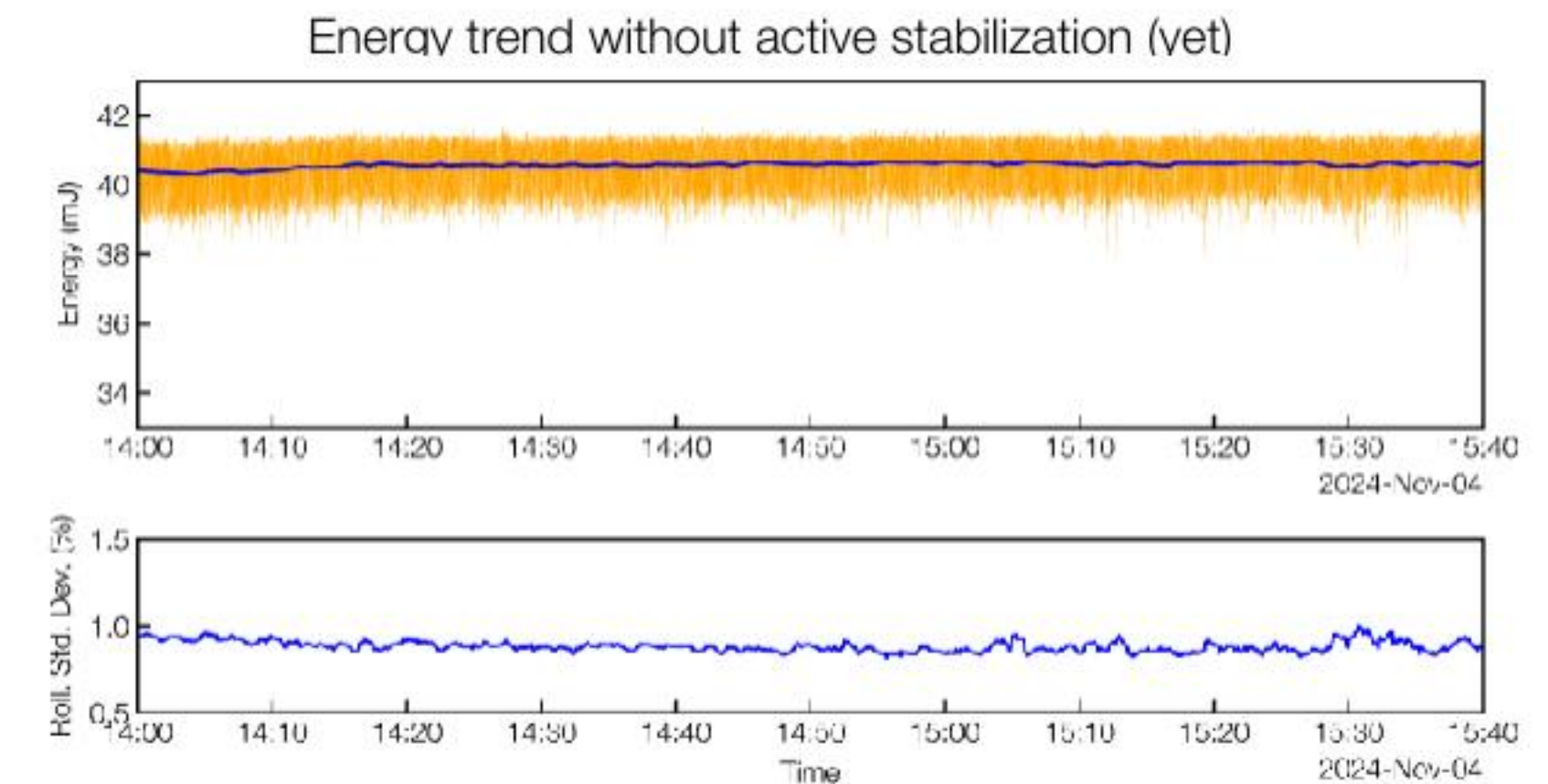
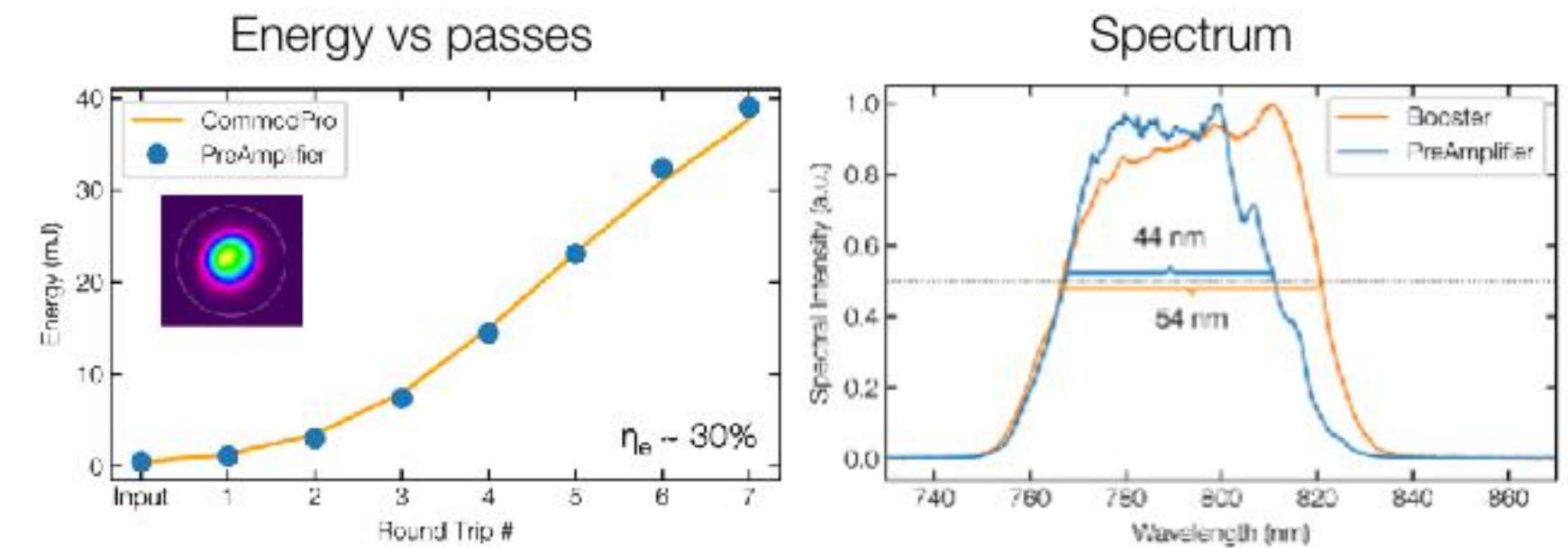
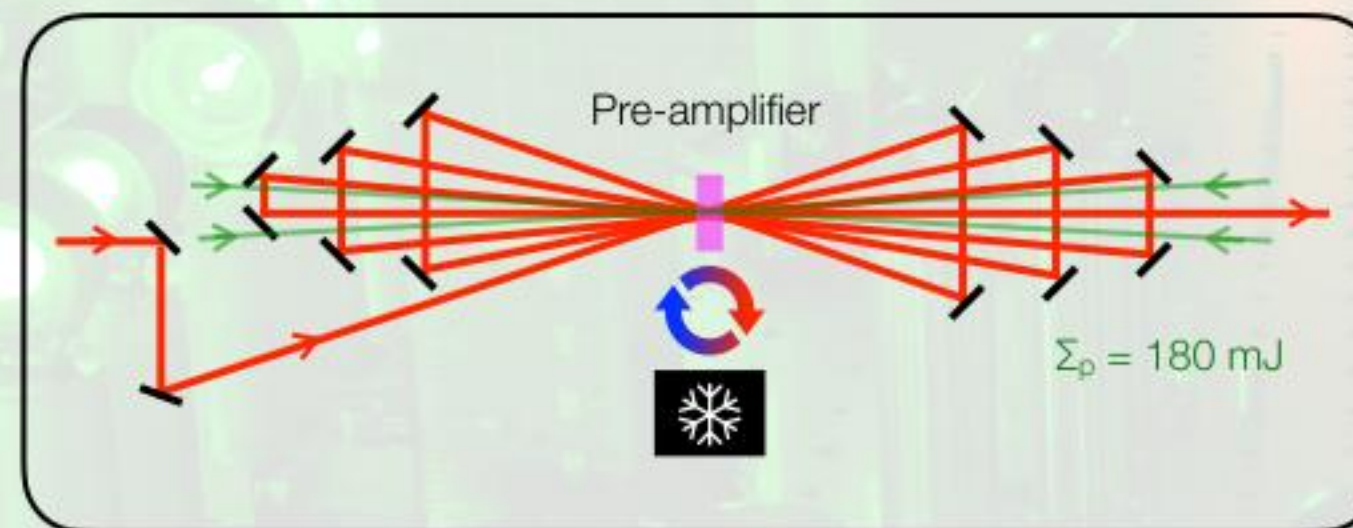
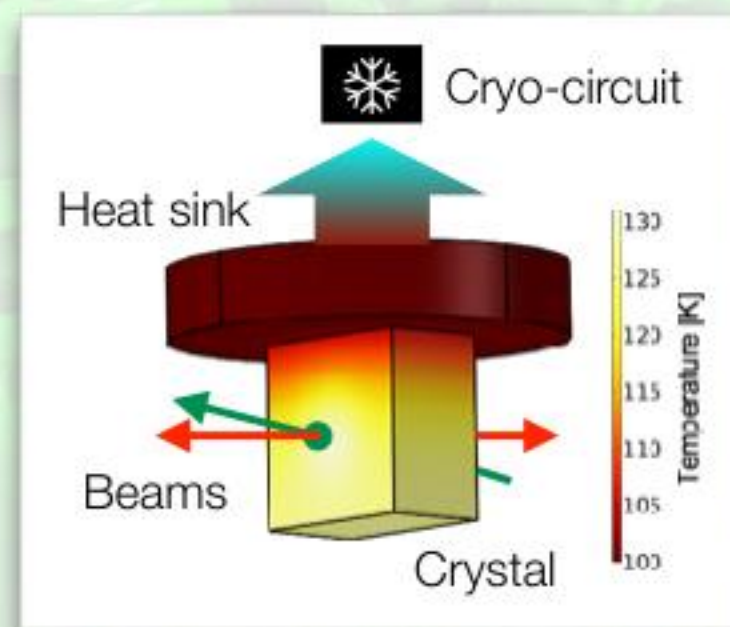


Franz X. Kärtner



Mikhail Pergament

- > With MERAPI the amplifier chain is operating at 1 kHz already
- > 7-pass cryogenic amplifier
- > Up to 40mJ of pulse energy (33% efficiency)
- > Supports 25fs bandwidth
- > Pumped by 4 x Coherent Revolution80 with up to 180W
- > Crystal bonding process from FS-CFEL group at DESY
- > Commercial low-vibration solid-state cryogenic cooler



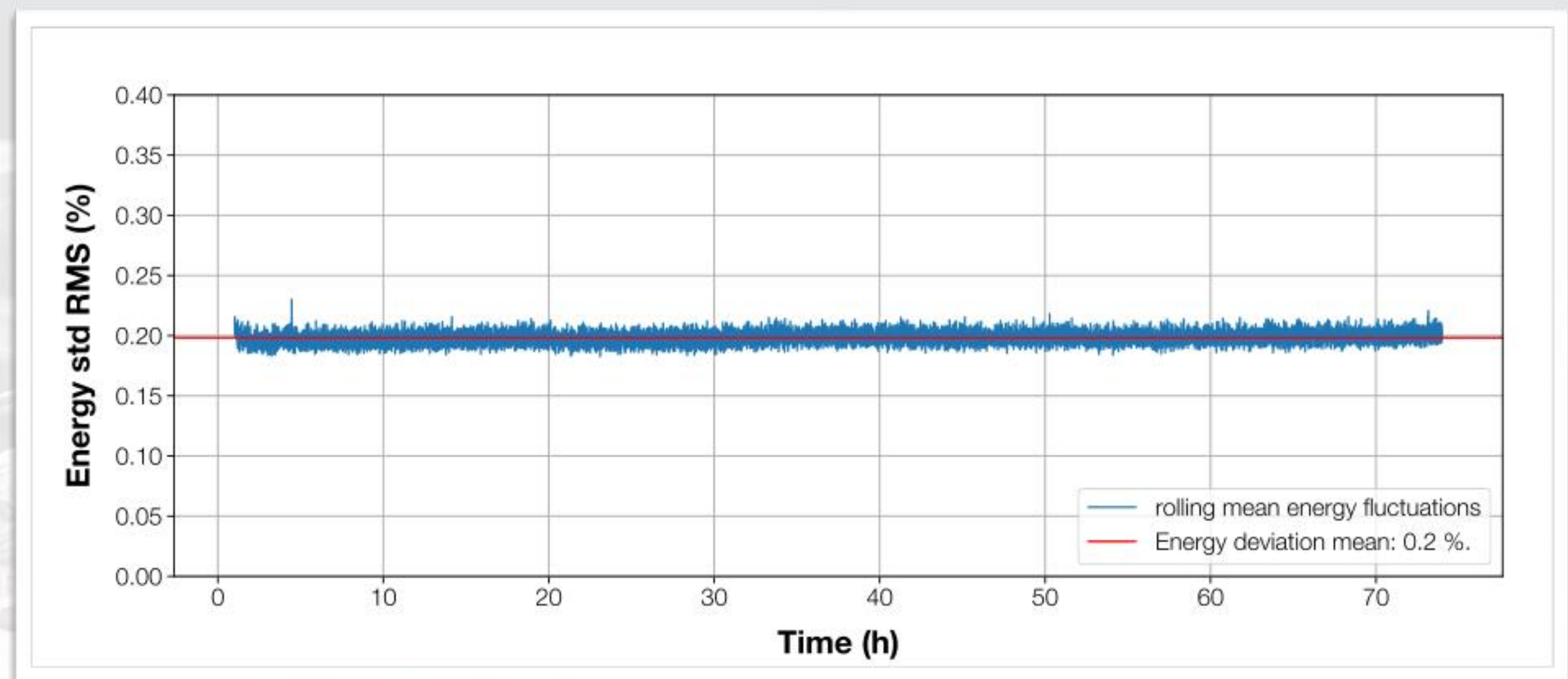
Thanks to Matthias Resch and his team



Selected pump lasers for 100 Hz operation

- > Innolas EVO Series
- > 1 kW (green) total pump power
- > 100W per system
- > Diode pumped
- > Excellent performance

Continuing to evaluate pump laser options for future kHz operation.



KALDERA

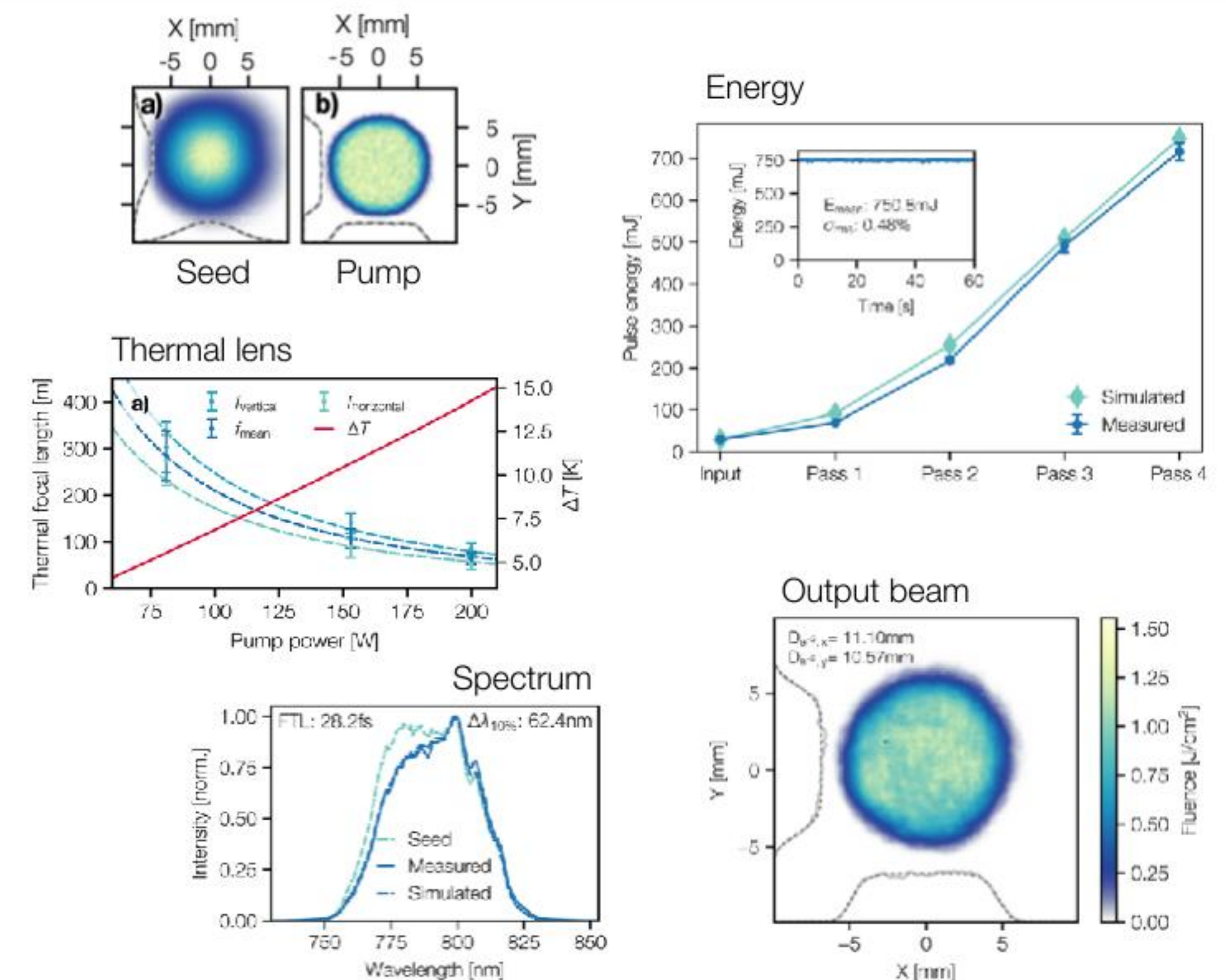
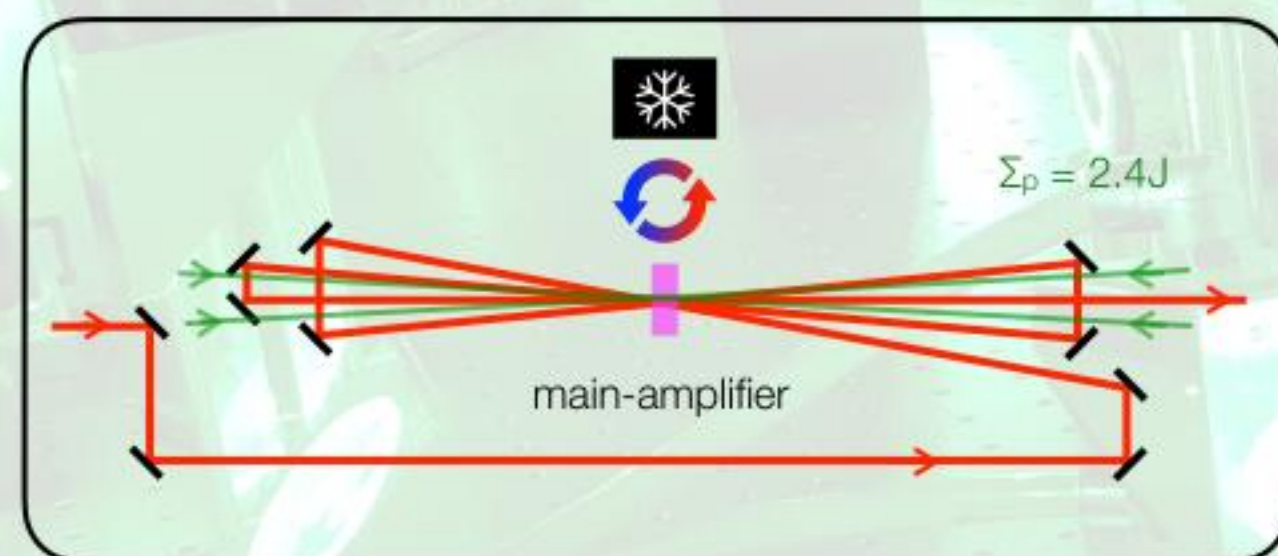
100Hz Amplifier 1

T. Eichner et al., Opt. Lett. 50, 4890 (2025)



First main amplifier (COLIMA)

- > All fully diode-pumped@100Hz
- > Saturated 4-pass cryogenic amplifier
- > 750mJ of pulse energy with efficiency 37%
- > Pumped by 4xEVO₄ from INNOLAS
- > Both gain and thermal behavior understood and engineered by simulations



KALDERA Compressor

Multi-layer gratings in an out-of-plane geometry

credit: C. Werle

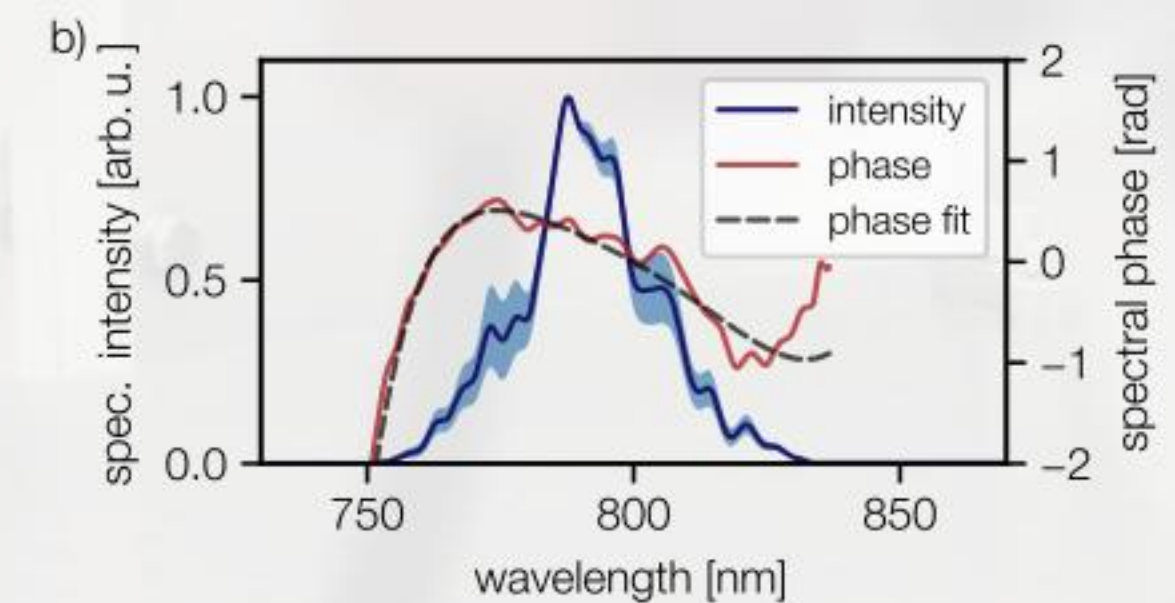
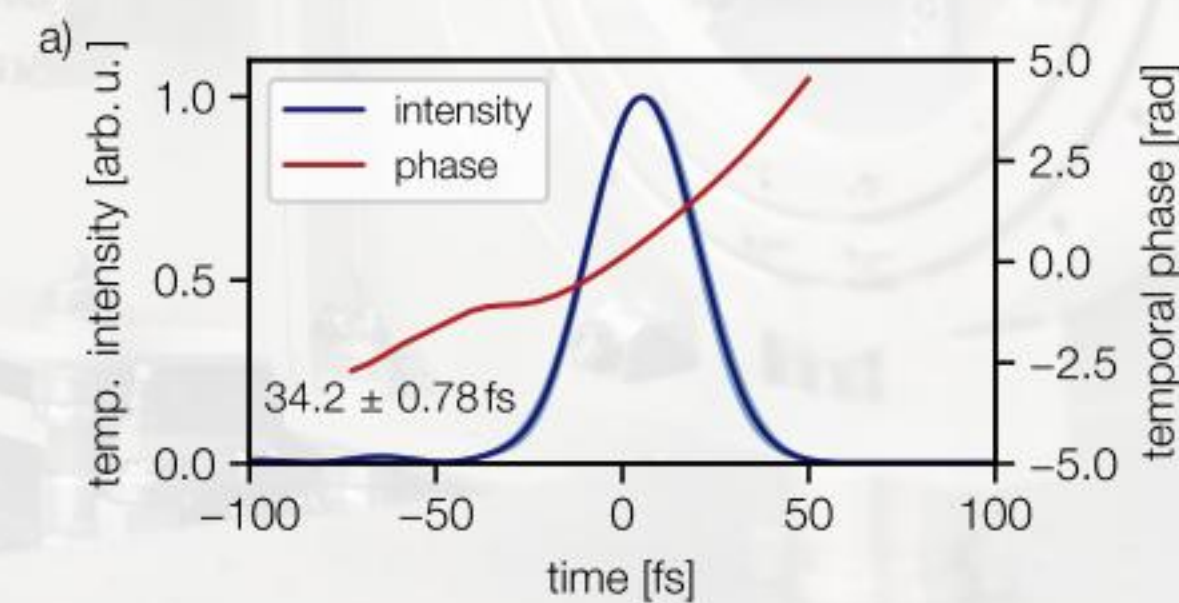
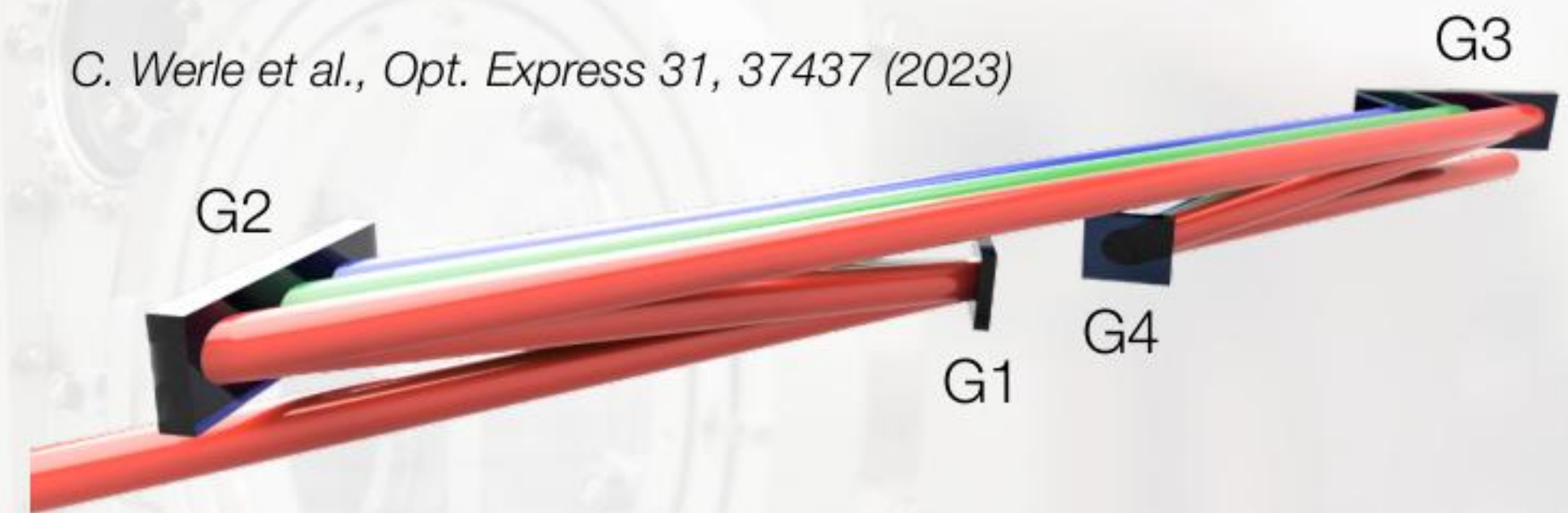


Current status:

- > Compressor supports 35fs, 100Hz, 1J-level
- > Many days of beam time with 10^6 shots / shift
- > Contrast measurement currently better than 10^6
- > (Integrated) compressor transmission >80%
- > Supports out of the box 34fs w/o any dazzler tuning (we expect <30fs after final tuning)

We plan to use the same concept for a future kHz version.

C. Werle et al., Opt. Express 31, 37437 (2023)



KALDERA & MAGMA

Scientific Engineering

Credit: L. Winkelman & team



- > Laser engineering and development
- > Full DESY-control integration from laser to LPA
- > Passive and active stabilization
- > Machine protection system (cryo-system, vacuum,...)
- > Support real time data analysis and DAQ with shot-to-shot capabilities, e.g., kHz cameras
- > FPGA data processing
- > In-house CAD engineering and FEM simulations

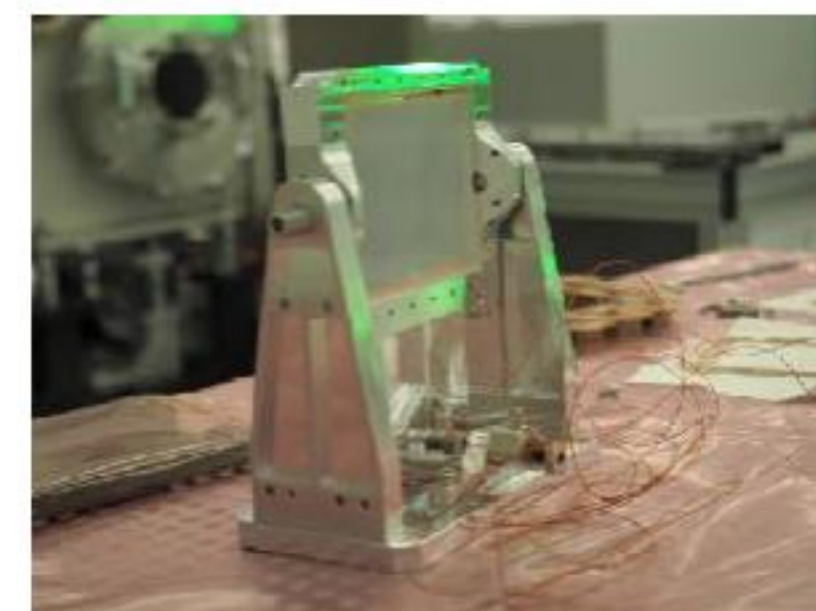


Vacuum chambers

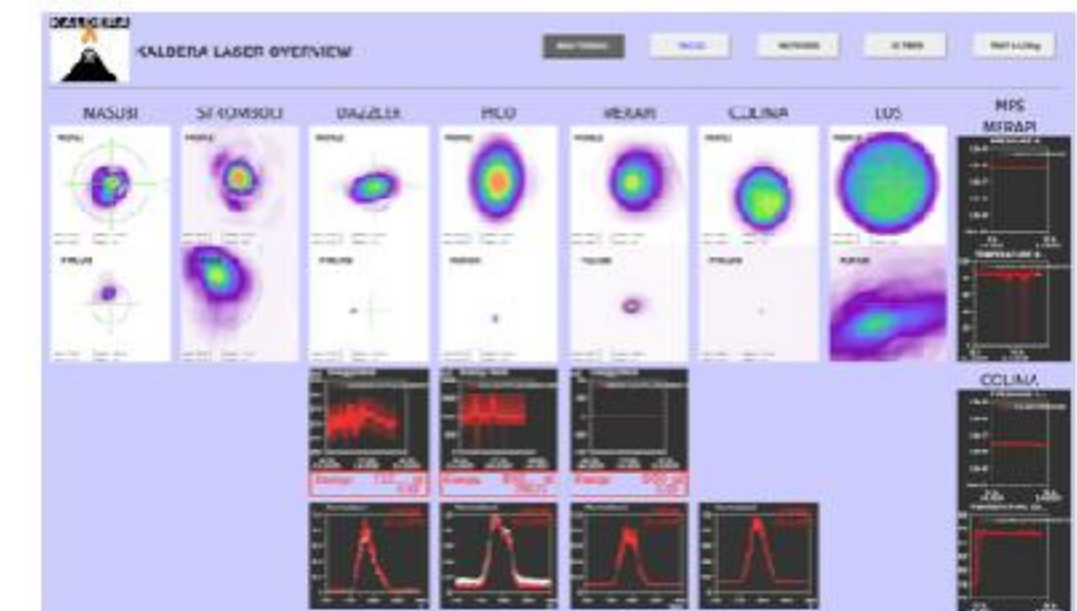
Laser and electron beam line design



Custom opto-mechanics



Control system: DOOCS

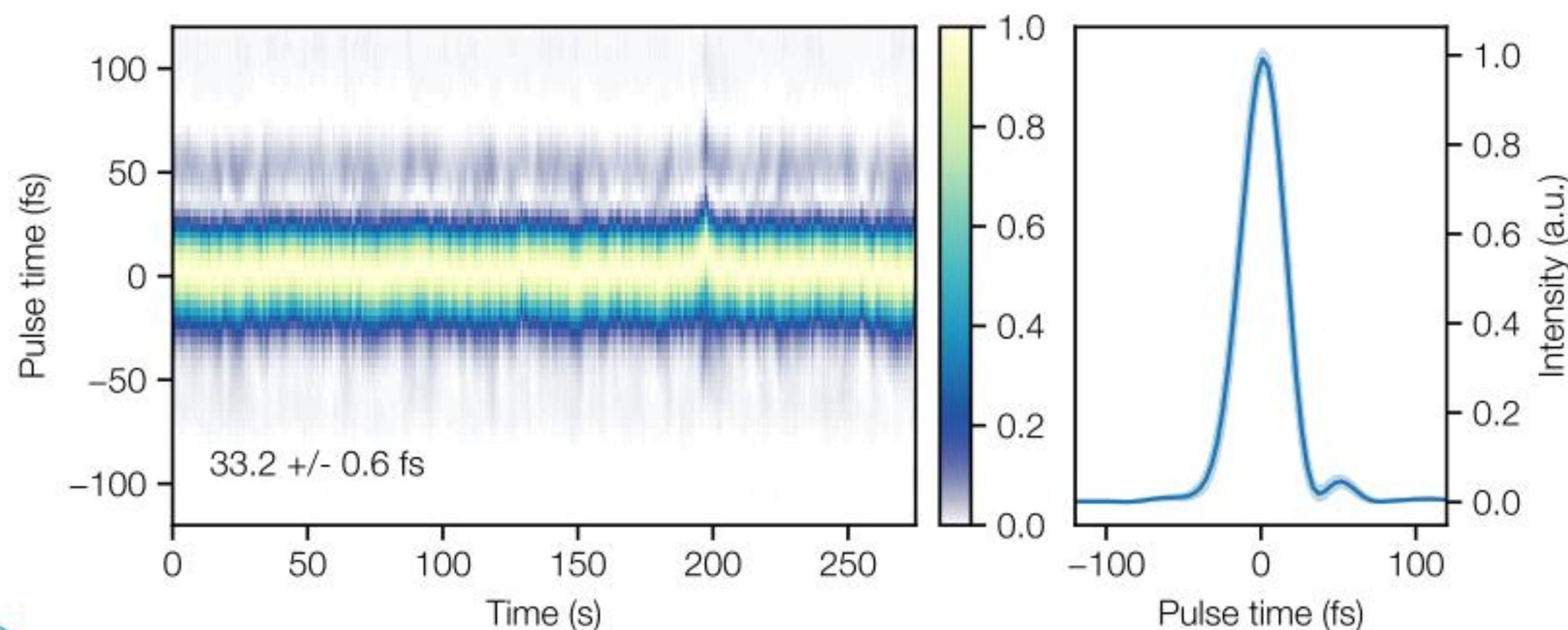


KALDERA Commissioning

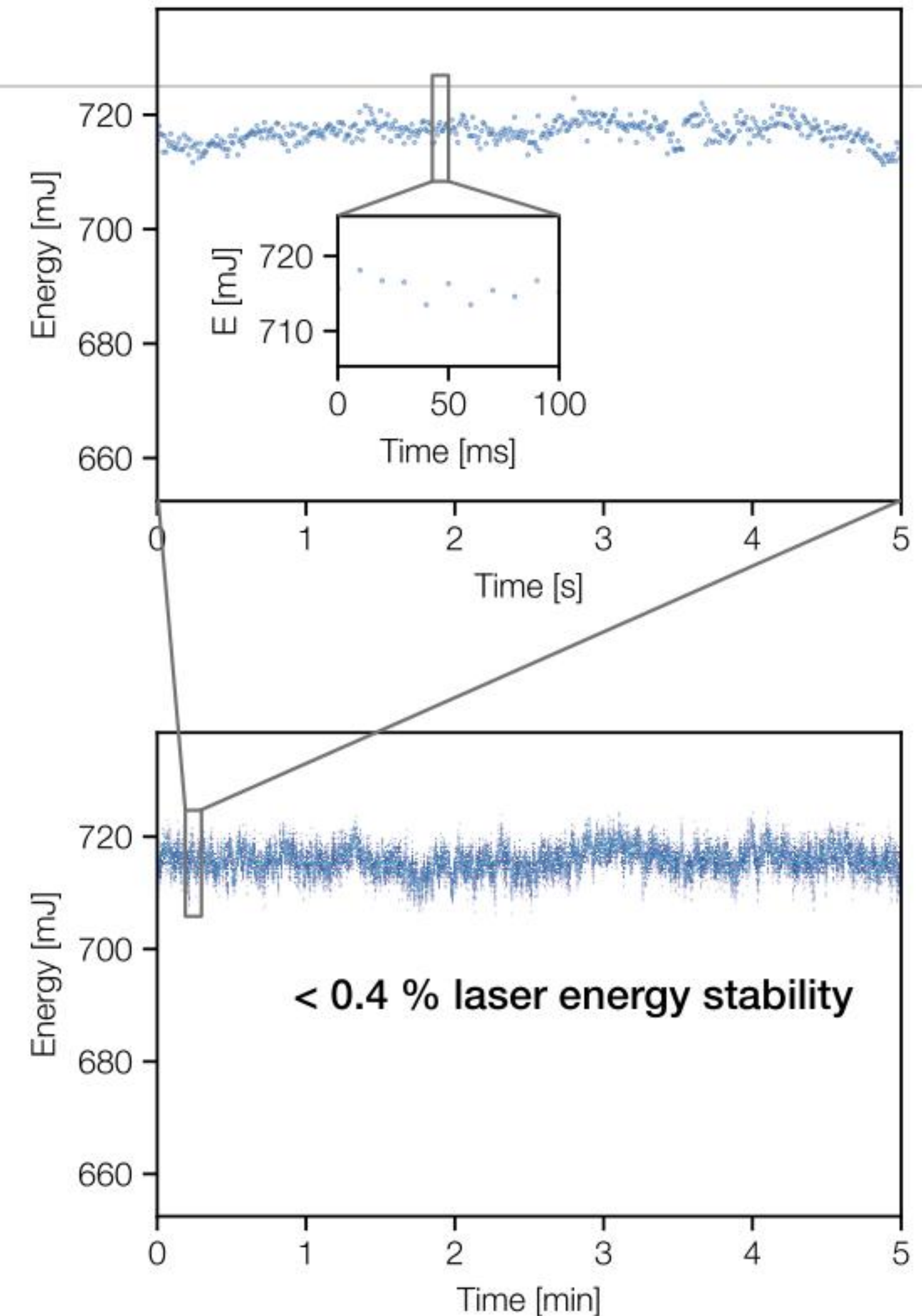
Laser performance & long-term operation

- ▶ Stable 100Hz operation over hours already possible
- ▶ Online monitoring of laser performance in control system
- ▶ Commissioning of 100 Hz diagnostics & DAQ
- ▶ So far, we use only passive stabilization

Shot-to-shot pulse length stability @ 100 Hz
and full (phase 1) energy



Shot-to-shot laser energy stability @ 100 Hz
Yet without active stabilization



MAGMA

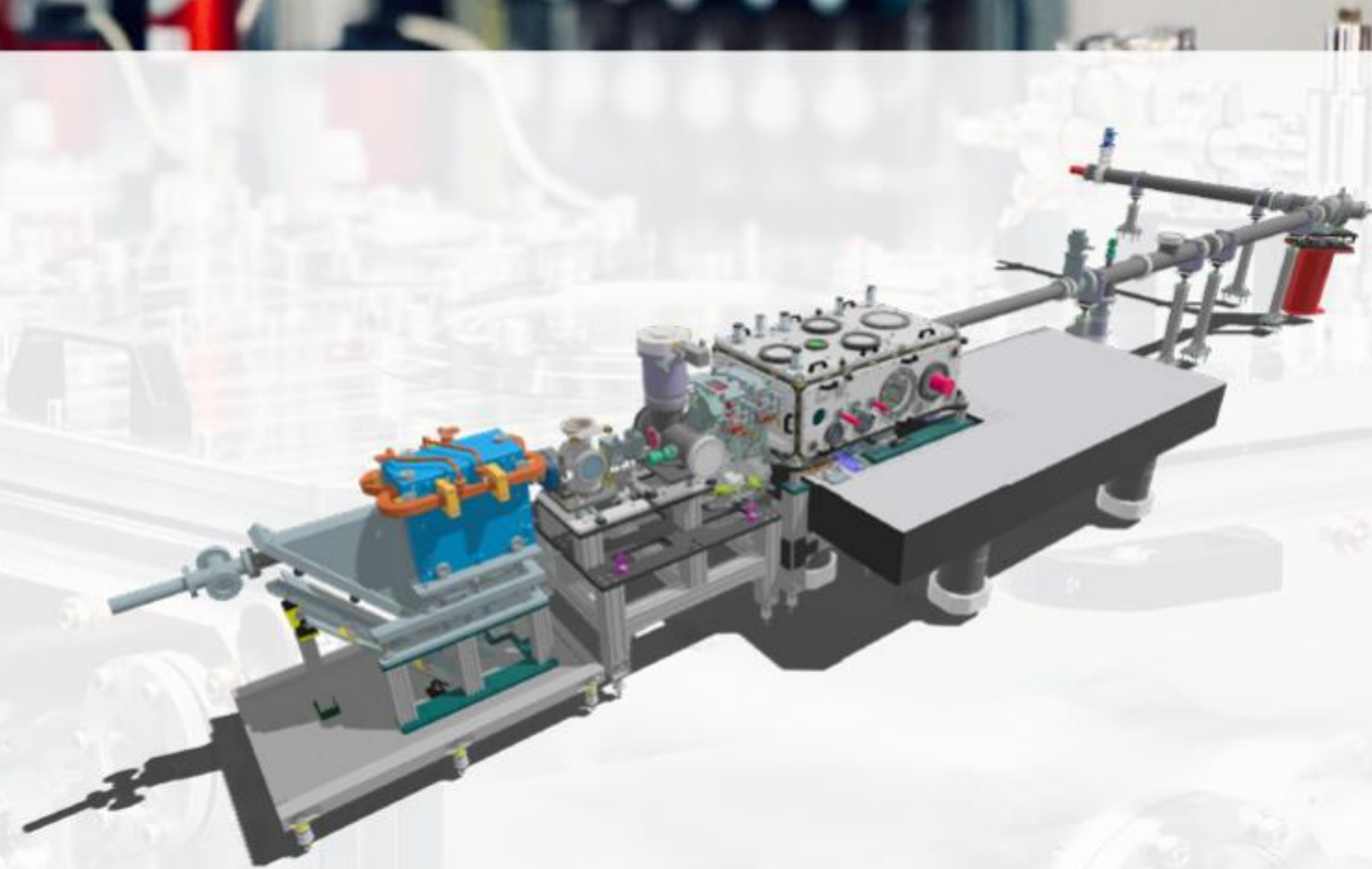
KALDERA Phase 1: LPA

Talk:
M. Kirchen, Mon 5:00pm,
Sala Biodola (Hotel Biodola)



Our mission

- > Phase1: 100 MeV @ 100 Hz
- > Completely integrated with laser system
- > Testbed for active stabilization systems



MAGMA

KALDERA Phase 1: LPA

Talk:
M. Kirchen, Mon 5:00pm,
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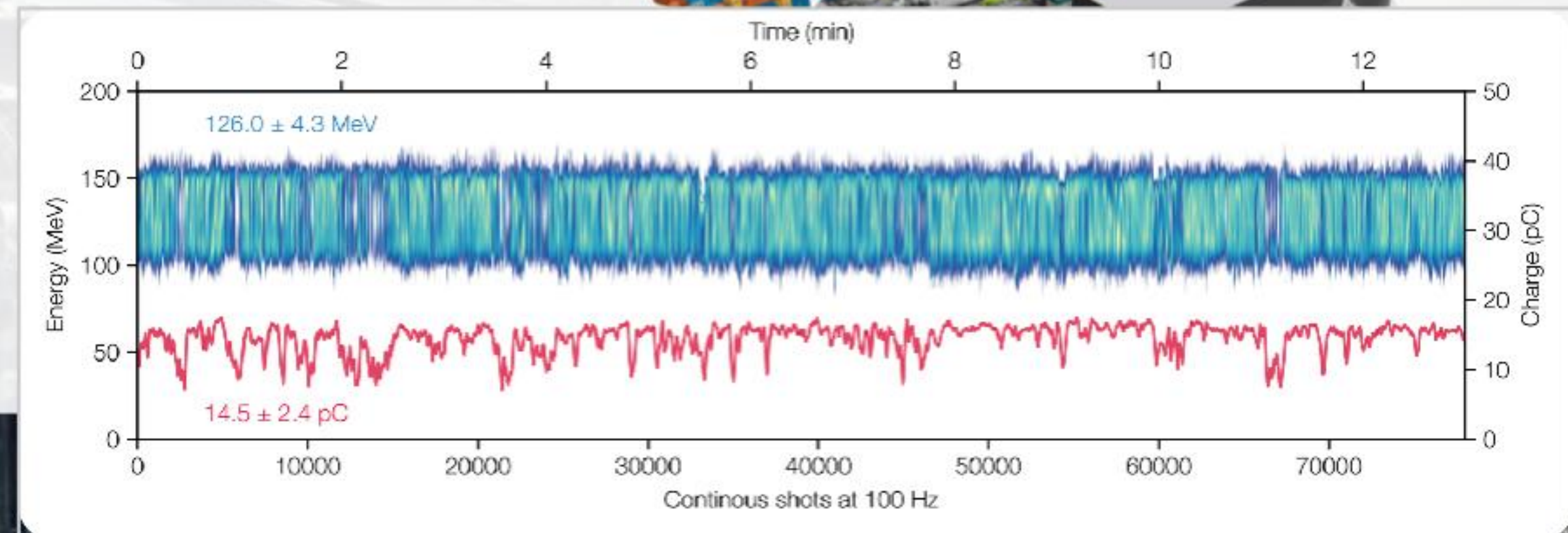


Our mission

- > Phase1: 100 MeV @ 100 Hz
- > Completely integrated with laser system
- > Testbed for active stabilization systems

Today

- > 1MShot and several μC integrated charge per shift
- > Around 120MeV, few-10pC
- > 100k shots in 10 minutes (which took us previously a full 24h shift)
- > See Manuel's talk for more details

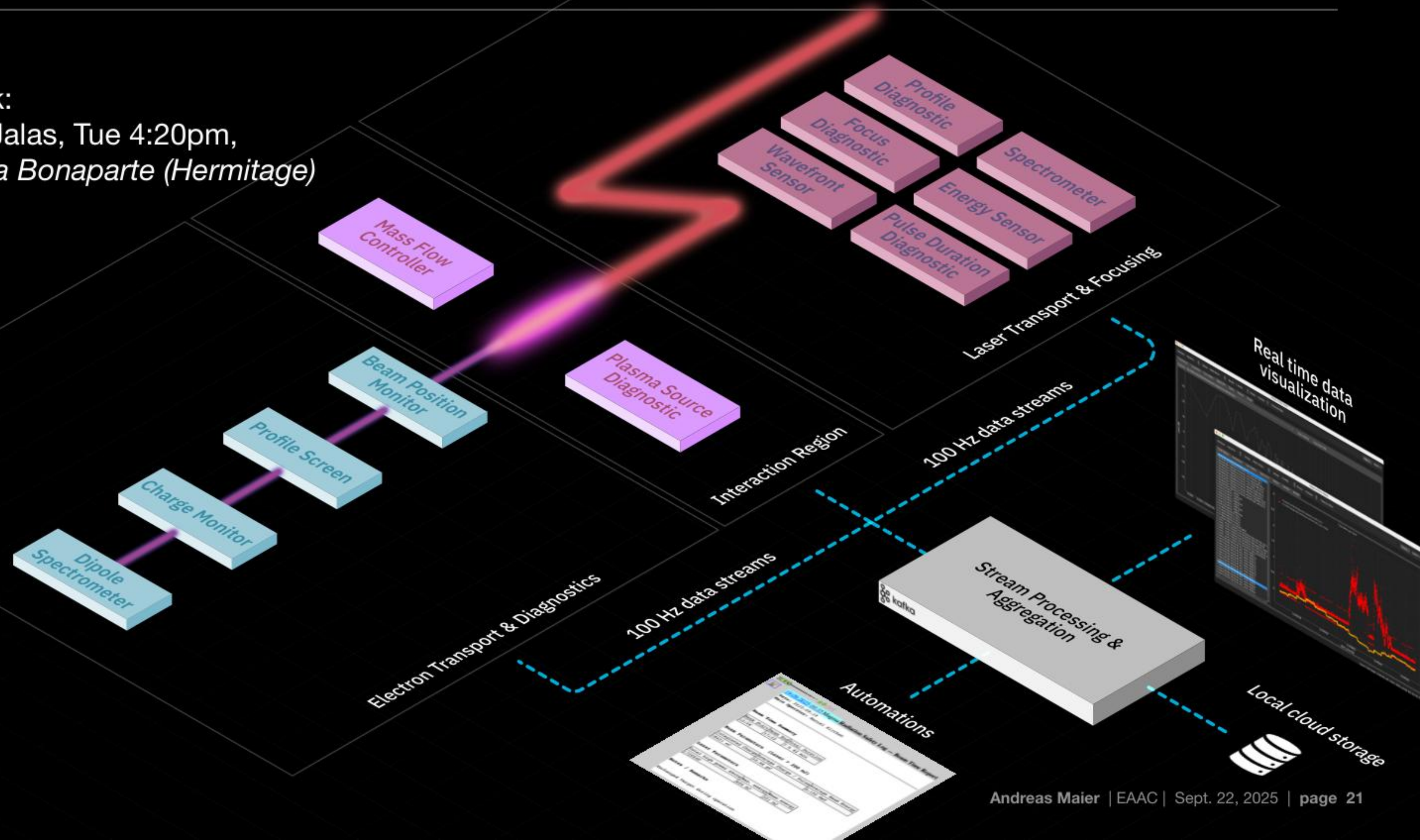


Data Driven LPA research

Realtime processing and analysis of 100 Hz LPA data



Talk:
S. Jalas, Tue 4:20pm,
Sala Bonaparte (Hermitage)



Data Driven LPA research

Realtime processing and analysis of 100 Hz LPA data



Talk:
S. Jallas, Tue 4:20pm,
Sala Bonaparte (Hermitage)



Live correlations @ 100Hz

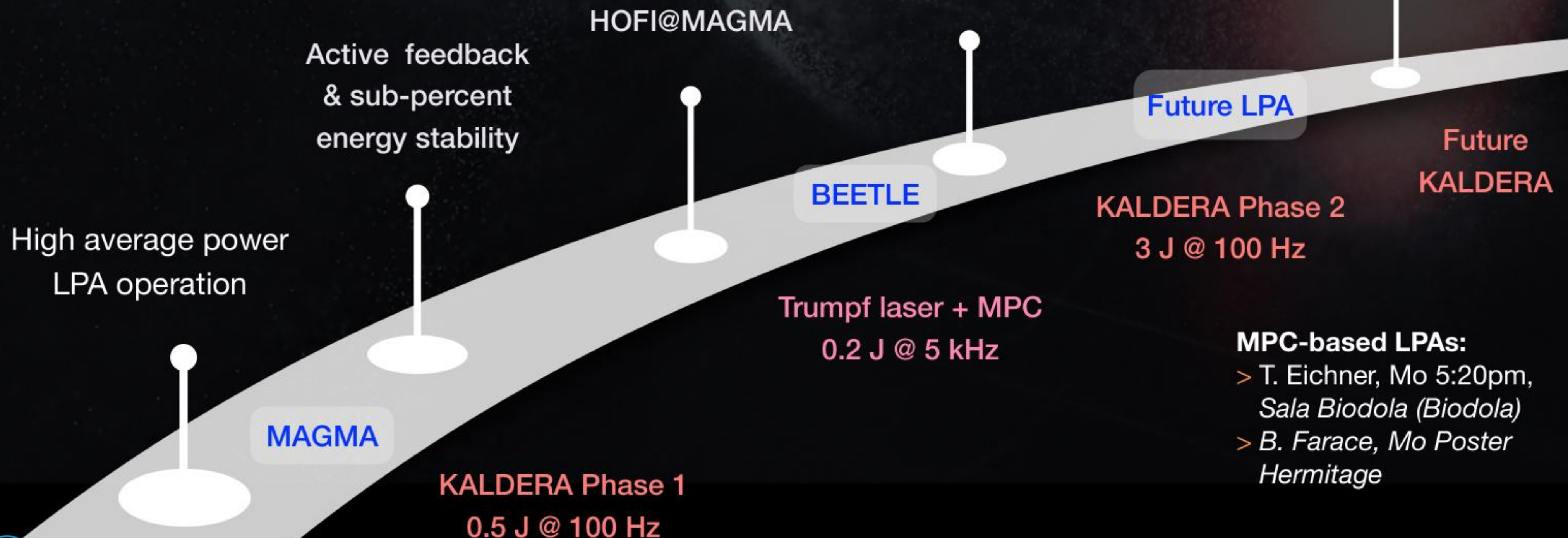


LPA Development Roadmap

Where to go from here



- > R. Shaloo, Tue 5:40pm,
Sala Maria Luisa (Hermitage)
- > A. Puchert, Wed. 6:20pm
Sala Bonaparte (Hermitage)

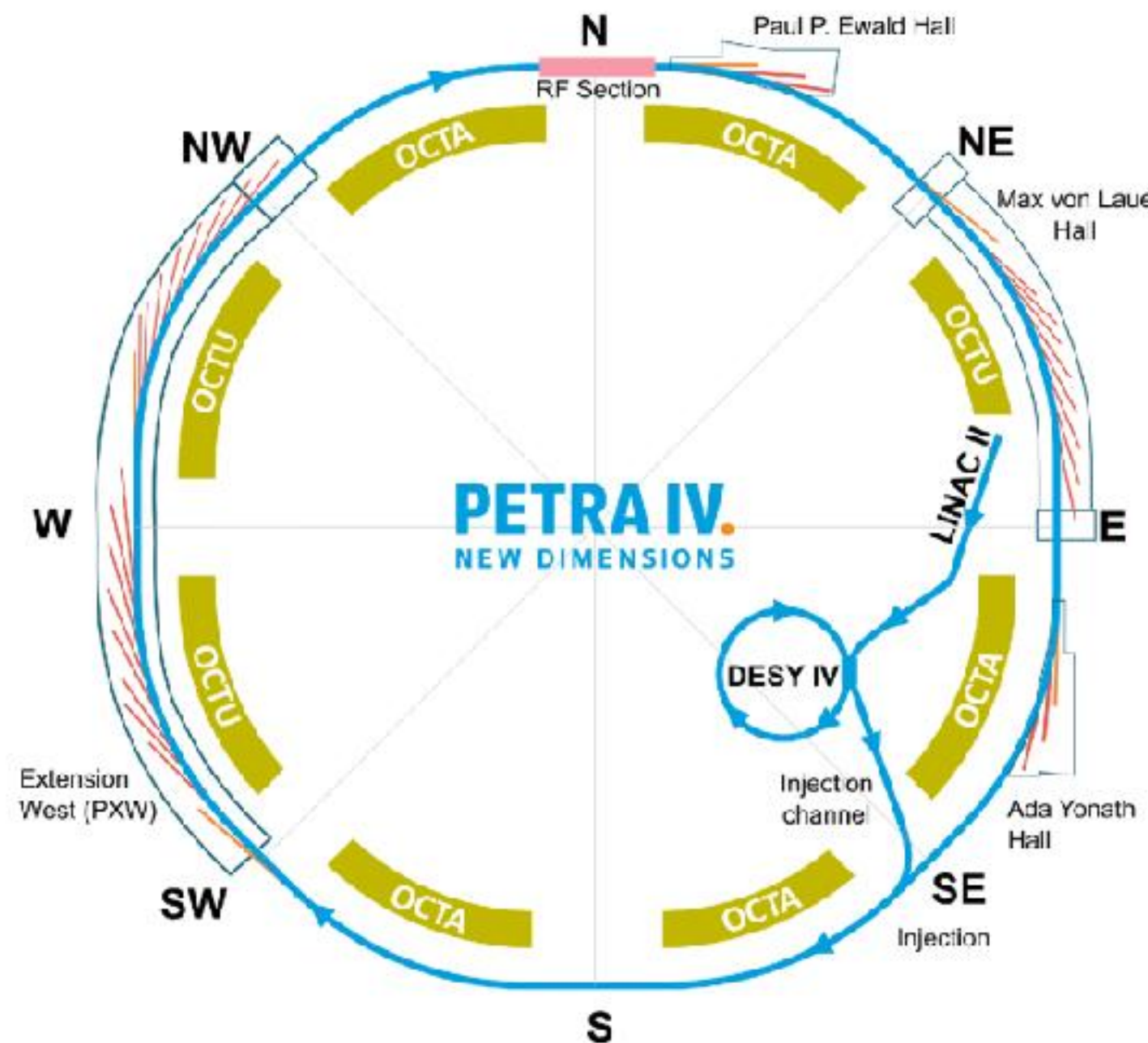


- MPC-based LPAs:**
- > T. Eichner, Mo 5:20pm,
Sala Biodola (Biodola)
 - > B. Farace, Mo Poster
Hermitage

Plasma Injector for PETRA IV

Based on KALDERA Laser Technology

- > A. Maier, Tue 4:20pm, Sala Bonaparte (Hermitage)
- > M. Thévenet, Wed 7pm, Poster
- > S. Antipov, Fri 11:30am, Plenary



PETRA III to PETRA IV Upgrade

- > 1.7 B€ project
- > Now a German infrastructure priority project
- > Completely refurbish the 2.3 km ring



Credit: A. Martinez de la Ossa et al., PETRA IV
Plasma Injector Conceptual Design Report

We need to master

- > Laser technology: 30J class laser @ 10Hz
- > HOFI guiding
- > Active energy compression

Energy compression to the permille-level demonstrated at LUX

P. Winkler et al. Nature 640, 907 (2025)

nature

Article

Active energy compression of electron beam

<https://doi.org/10.1038/s41586-025-08772-y>

Received: 19 November 2024

Accepted: 11 February 2025

Published online: 09 April 2025

Open access

Check for updates

Radio-frequency are an important medical application of microwaves. The brightness of the beam produced by a laser-plasma accelerator is a substantial energy spread. Using a radio-frequency to improve the resonance synchronism, the magnitude of the synchrotron radiation is significantly reduced.

In a laser-plasma accelerator, the interaction of a high-power laser pulse with a plasma creates a trailing density modulation wave, which supports electric fields several orders of magnitude larger than those provided by modern RF accelerators. The plasma wave can trap electrons and accelerate them to relativistic energies.

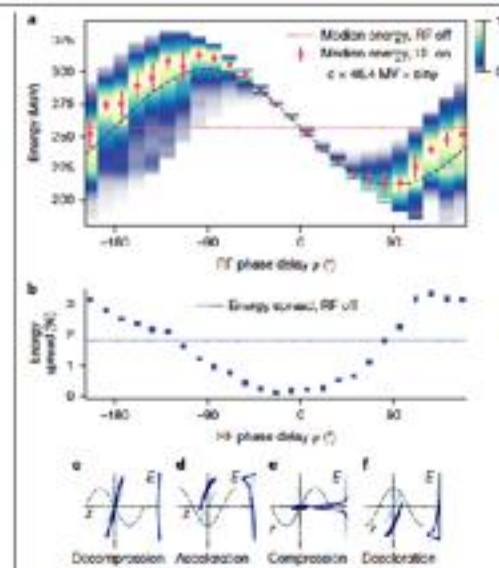


Fig. 2 Phase scan between laser plasma electron beam and RF field. **a**, Plot of energy (MeV) versus RF phase delay (°) for a laser-plasma electron beam. The energy spread is reduced by a factor of 10. **b**, Plot of energy spread (%) versus RF phase delay (°). The energy spread is reduced by a factor of 10. **c–f**, Schematic diagrams of electron beam compression and acceleration at different RF phases.

the chirp and, thus, energy spread. The opposite effect happens at a phase of 180° , at which the slope of the RF is inverted: electrons at the head of the bunch are now accelerated, whereas electrons at the back of the bunch are decelerated, effectively increasing the chirp and broadening the spectrum. Around $\sim 90^\circ$, the bunch is collectively decelerated and accelerated, respectively, which shifts the energy spectrum.

Notably, we find the smallest energy spread not at 0° but at a slightly shifted phase of -23.4° (Fig. 2b), which can be understood as follows. The second-order dispersion of the chicane adds a small curvature to the linear energy chirp. Therefore, we need to operate the RF slightly below 0° , at which the small curvature of the sinusoidal RF field just compensates the nonlinear chirp (Methods). Operating instead at 0° , the RF field is almost linear and cannot compensate the curvature of the chirp, resulting in a larger energy spread. In general, owing to these nonlinearities, there is a unique pair of amplitude and phase that can be calculated analytically (Methods) and results in the smallest possible energy spread.

At the optimum set point with minimum energy spread, we recorded about 1,000 shots with the RF turned off and on, shown in Fig. 3. With the RF on (Fig. 3a), the energy jitter reduced by a factor of 72 from 3.5% to 0.048% and the energy spread reduced by a factor of 18 from 1.8% to 0.097%. Operating at a phase of -23.4° , the fully energy-compressed beam was shifted from a median energy of 257 MeV (RF off) to 275 MeV (RF on). The energy-compressed beams have a mean charge of 12 pC (12 pC r.m.s.). The peak spectral density reached as high as 70 pC per MeV. About 50% of all shots feature a sub-permille energy spread (extended data Fig. 1). Some shots were compressed to an energy spread as small as 0.058%, which is at the ultimate resolution limit of our electron spectrometer, with compression, the charge provided inside a $\pm 1\sigma$ window of the median energy improved from 18.1% to 99.9%.

These results correspond to the best energy compression settings in the experiment, but we can further explore different capabilities of the set-up.

For example, searching the electron bunch more lowers the energy chirp and thus reduces the required RF amplitude and thus power to operate the cavity. As the longer bunch then covers a larger phase of the RF, nonlinearities will reduce the energy compression performance. We tested this behaviour ($L_{\text{plasma}} = 170$ mm, amplitude 28 MV) and could still reduce the energy jitter and spread to 0.09% and 0.13%, respectively, while consuming a factor of three less RF power.

Furthermore, we can vary the RF phase to fine-tune the target energy within a several-percent range without notable loss of compression performance.

In summary, we provide electron beams with a performance in energy jitter and spread previously only obtained from modern RF accelerators, opening up widespread deployment of laser-plasma accelerator technology.

An important application for such an energy-compressed laser-plasma electron beam is as injector for a future synchrotron storage ring.

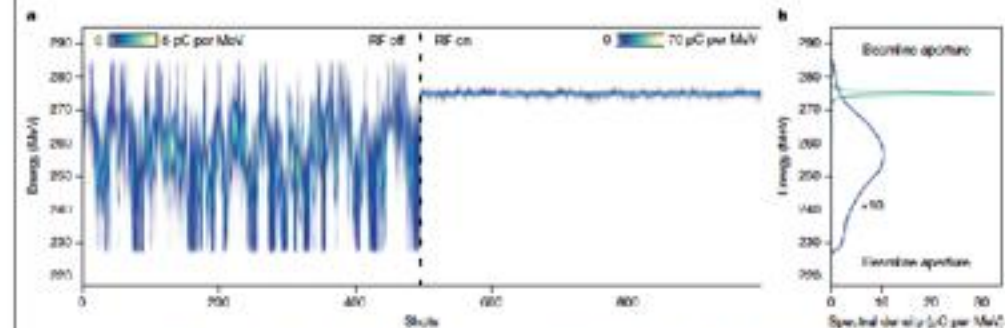


Fig. 3 Active energy compression. **a**, Series of approximately 1,000 energy spectra recorded with the RF off and on. **b**, The energy spread is reduced by a factor of 18. The energy spread is reduced by a factor of 18. The energy spread is reduced by a factor of 18.

Nature | Vol 640 | 24 April 2025 | 909

- > A. Maier, Tue 4:20pm, Sala Bonaparte (Hermitage)
- > M. Thévenet, Wed 7pm, Poster
- > S. Antipov, Fri 11:30am, Plenary



Phase 2: 100 Hz, 3J, 30 fs

- > New Stretcher under development
- > Main amplifier 2 („ARENAL“):
 - > Under development
 - > All pump lasers are ready (almost 1 kW)
- > 4J / kW-ready compressor
 - > Scaled version of TAUPO
 - > under development (expected 2026)



Related Contributions From DESY Group

(not yet highlighted)

Theory & Simulations

Xingjian Hui, Mon 4:20pm, *Sala Elena*,
“All-optic In-plasma Staging of Laser-Wakefield Accelerators Using Density Tailoring”

M. Thévenet, Mon 5:40pm, *Sala Maria Luisa*
“Resonant Emittance Mixing of Flat Beams in Plasma Accelerators”

M. Thévenet, Tue 5:40pm, *Sala Elena*
“Mainstreaming Start-to-End Realistic Simulations in Plasma Accelerator Research”

M. Thévenet, Wed Poster
„The plasma injector for Petra IV: Conceptual Design Report“

FLASHForward

JP Diaz, Mon Poster
„Temperature diagnostics for high-repetition-rate plasma accelerator sources“

J. Björklund Svensson, Mon Poster
„Experimental Generation of PWFA-suitable Bunch Current Profiles by Arc-like Bunch Compressors“

J. Wood, Mon Poster
„Physics Considerations for a Plasma Booster Stage for the European XFEL“

J. Beinortaitė, Mon Poster
„Long-duration ion motion effects in beam-driven plasma-wakefield accelerators“

L. Boulton, Tue 5:40pm, *Sala Bonaparte*
“Advanced Controls and Machine Learning at FLASHForward”

J. Wood, Wed 4:40pm, *Sala Maria Luisa*
„Latest Results from the FLASHForward Experiment“

Applications

K. Poder, Tue 5:00pm, *Sala Bonaparte*,
“Muon scattering tomography with laser-plasma-accelerator-driven muon source”

K. Poder, Tue 5:40pm, *Sala Bonaparte*,
“Compact all-optical precision-tunable narrowband hard Compton X-ray source”

C. Mariani, Wed. Poster
„Optimisation of Inverse Compton Scattering via spatio-temporal tailoring of the scattering pulse“

S. Bohlen, Wed Poster
„Radiation Safety Challenges and Detector Solutions for Plasma Accelerators“





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Group Leader

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Thanks

To the whole plasma crew at DESY

