Plasma Accelerator Development

Experimental Perspective at DESY

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for slide material

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

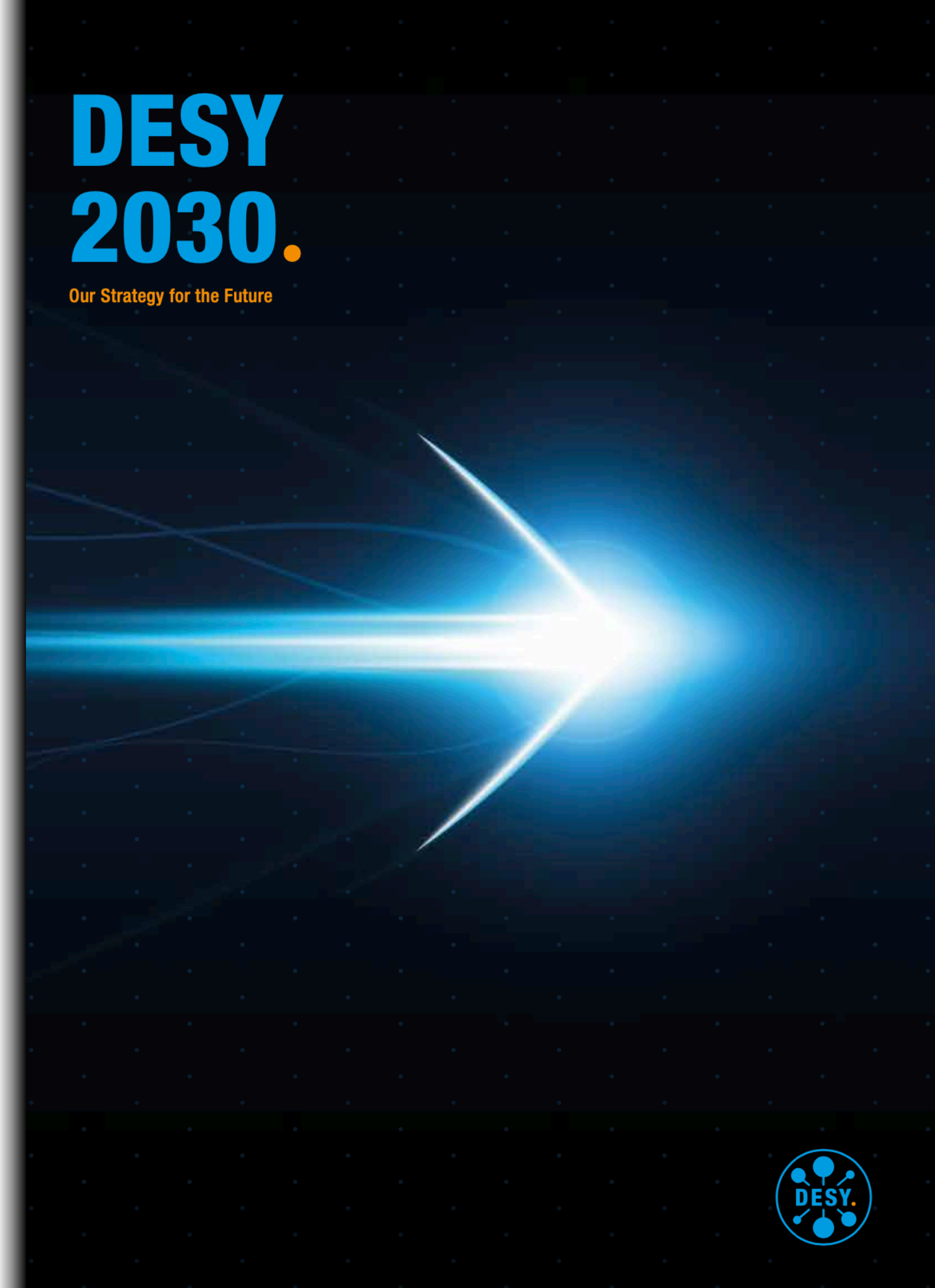
DESY.

Photo: K. Sjobak

Research Focus At DESY

“Our Strategy for the Future”

- **Photon Science**
  “Decoding molecular structures”
- **Particle Physics**
  “Understanding the origin of mass”
- **Astroparticle Physics**
  “Understanding cosmic evolution
- **Novel Accelerator Development**
  “Building the machines of the future”
- **Collaboration / Innovation / Inspiration**
  “We create places for exchange and ideas”



Plasma Acceleration at DESY is Growing

A Hub of Activity for Laser- and Beam-Driven Plasma Accelerator Development

FLASHForward ▸▸

FLASH. European XFEL

Develop a Self-Consistent Plasma Accelerator Stage as an FEL Energy Booster

High Beam Quality
Low energy spread
Emittance preservation

High Efficiency
Transfer-efficiency
Driver depletion

High Average Power
Bunch-train pattern
High repetition rate

PLASMED X

Compact High-Energy X-Ray Source for Advanced Medical Imaging

Compact Source
All-optical design
10-TW scale driver

Tuneable Narrow Bandwidth
Active Plasma Lens Tailoring
Bandwidth stabilisation
Continuous tuneability

Application
X-Ray Fluorescence Imaging
of Gold nanoparticles

LUX

Merging Plasma-Acceleration with Modern Accelerator Technology

Robust & Reliable Accelerator
Driven by Angus laser system
300 MeV @ 1 Hz over 24h
< 1% energy spread demonstrated

Advanced Plasma Source
Gas density and composition tailoring
Downramp-assisted Ionisation injection
Optimal beam loading

Machine-Learning-Driven
Bayesian Optimisation
Predictive modelling

KALDERA

DESYs New Flagship Laser and Next-Generation Laser-Plasma Accelerators

Next-Generation 100 TW System
3J in 30 fs @ up to 1 kHz
Active stabilization techniques
Improved stability and performance

High-Average Power Electrons
High-average power plasma source
< 1% energy spread & energy stability
Increased energy via guiding

Unprecendented Stability
Laser-to-electron feedback control
Autonomous tuning with ML
Long-term operation

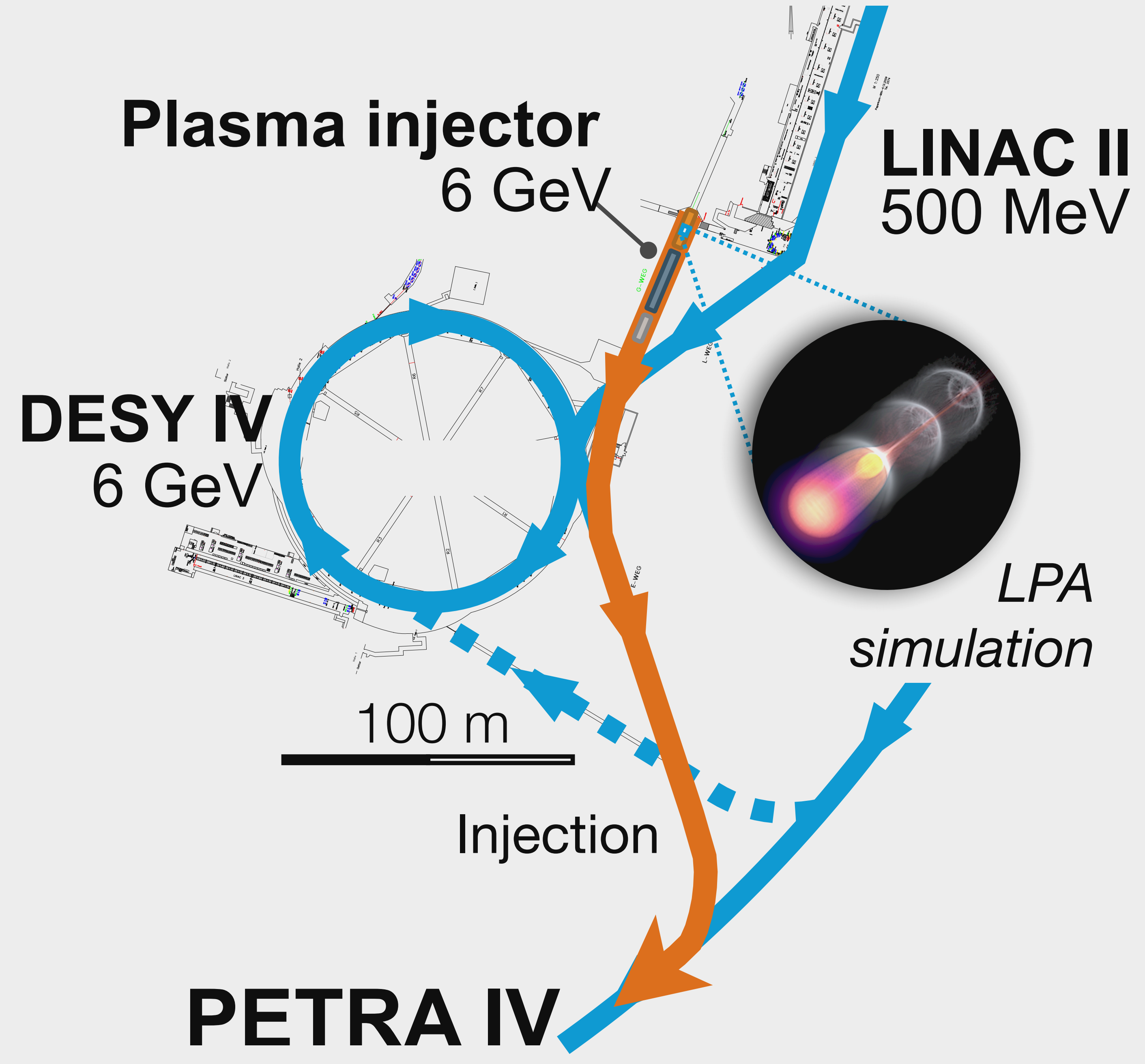
PETRA-IV Plasma Injector

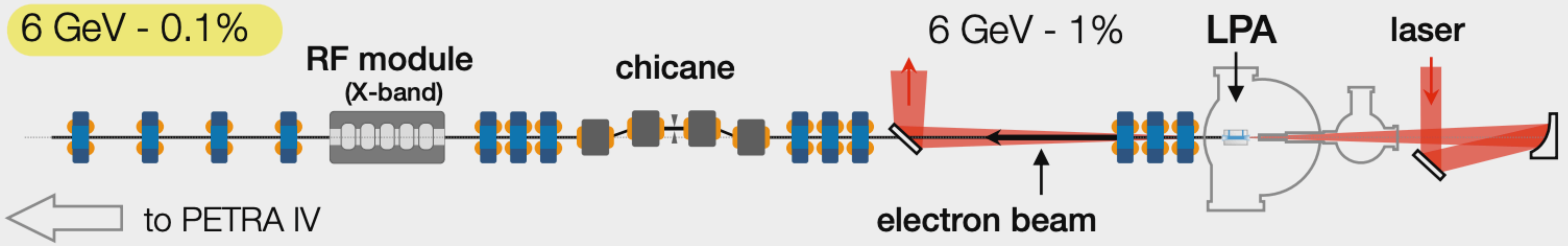
Efficient 6 GeV LPA-based injection system for PETRA-IV

Laser Upgrade
Petawatt upgrade to KALDERA
> 30 Hz
24/7 reliable operation

Plasma Source Development
Controlled injection
Plasma waveguiding
High-quality beam generation

Energy Compression Beamline
Reduce energy post-acceleration
Injection into PETRA -IV storage ring
> 2.7 nC/s





DESY. Plasma Accelerator Roadmap

Plasma-based particle accelerators for scientific and societal applications

LPA Applications
Medical
Industrial

10 kW Avg. Power
Pulsed MHz operation

Energy Compression
Post LPA beamline
Energy compression
Increased stability

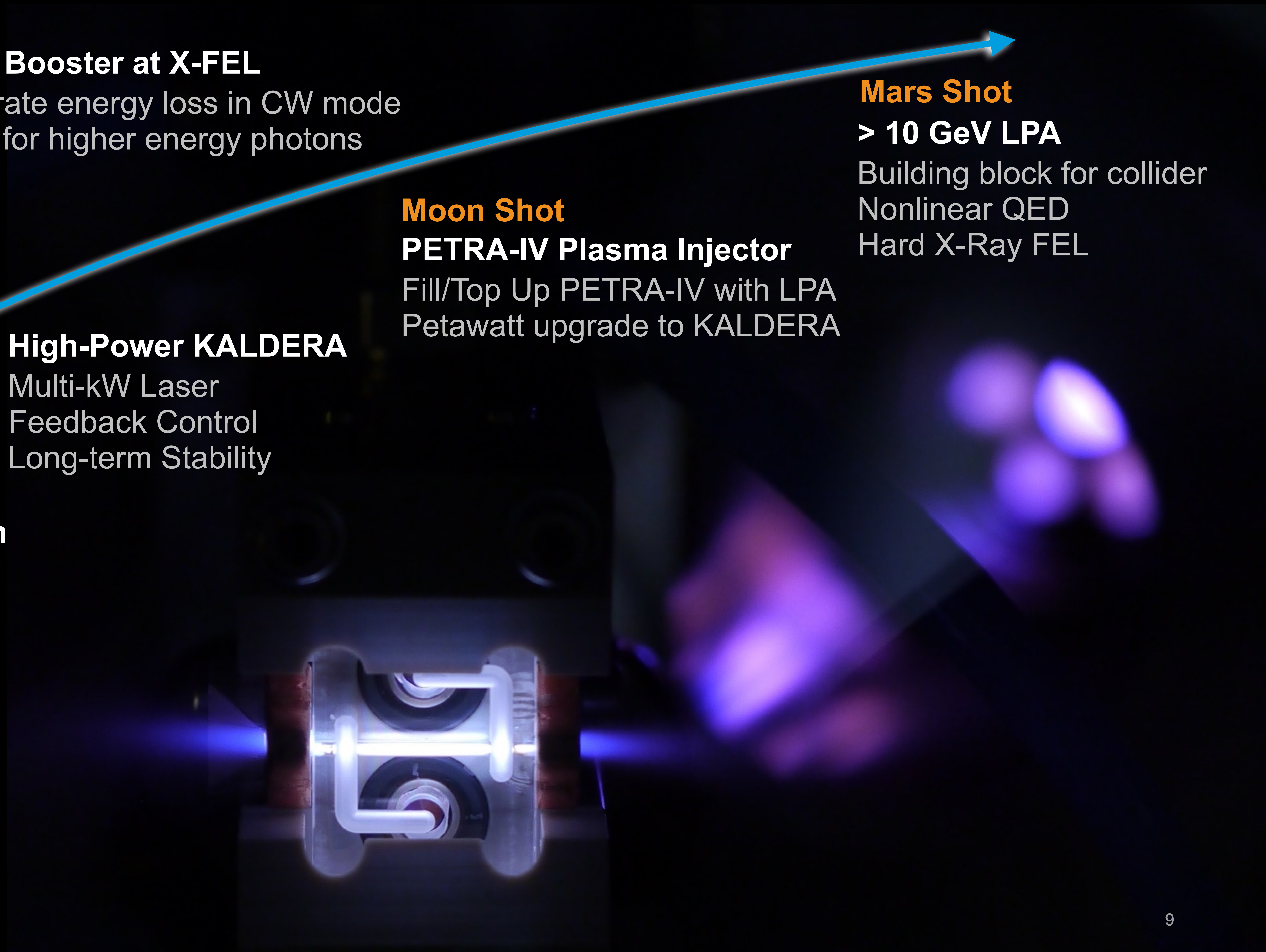
All-In-One Plasma Stage
High Efficiency
High beam quality
High average power

High-Power KALDERA
Multi-kW Laser
Feedback Control
Long-term Stability

Plasma Booster at X-FEL
Recuperate energy loss in CW mode
Booster for higher energy photons

Moon Shot
PETRA-IV Plasma Injector
Fill/Top Up PETRA-IV with LPA
Petawatt upgrade to KALDERA

Mars Shot
> 10 GeV LPA
Building block for collider
Nonlinear QED
Hard X-Ray FEL



Common Ground: Opportunities for Collaboration

Experimental Perspective

Advanced Laser Diagnostics
Measurement of spatiotemporal couplings. On-shot and dedicated diagnosis

Neutral Gas Source Tailoring
Towards developing robust and tuneable plasma sources

Beam Extraction and Manipulation
Post-accelerator Beamline components: Active plasma lenses / plasma-based laser beam dumps

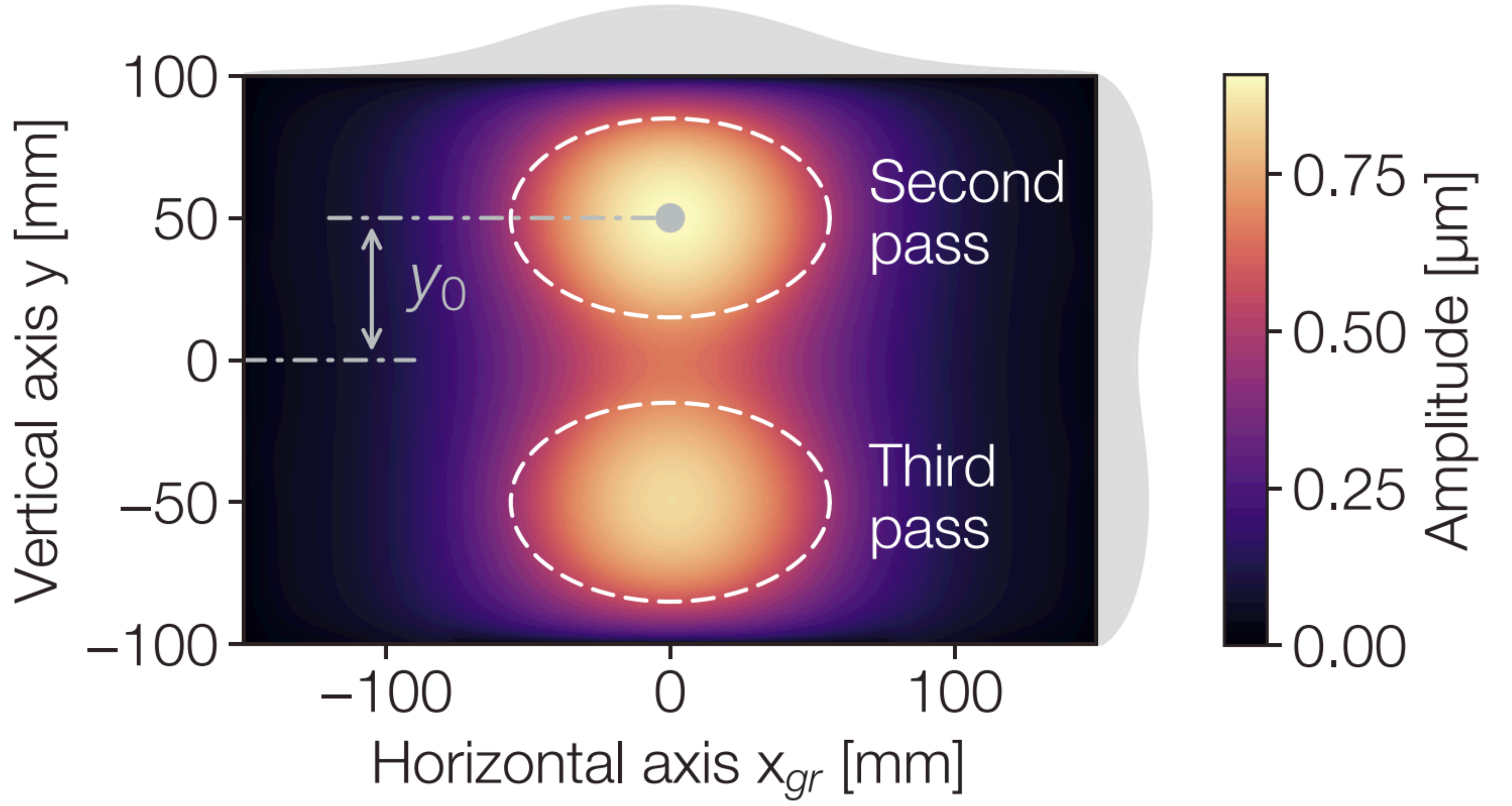
Control and Stabilisation Techniques
Advanced experimental control, opitimization and active stabilization

Advanced Laser Diagnostics

Precision measurements of laser pulse spatio-temporal couplings

Spatio-temporal couplings not only lower peak intensity but can significantly impact the generated electron beams [1,2]

Can be introduced through misalignments, chromatic elements or through heating of components at higher average powers [3]



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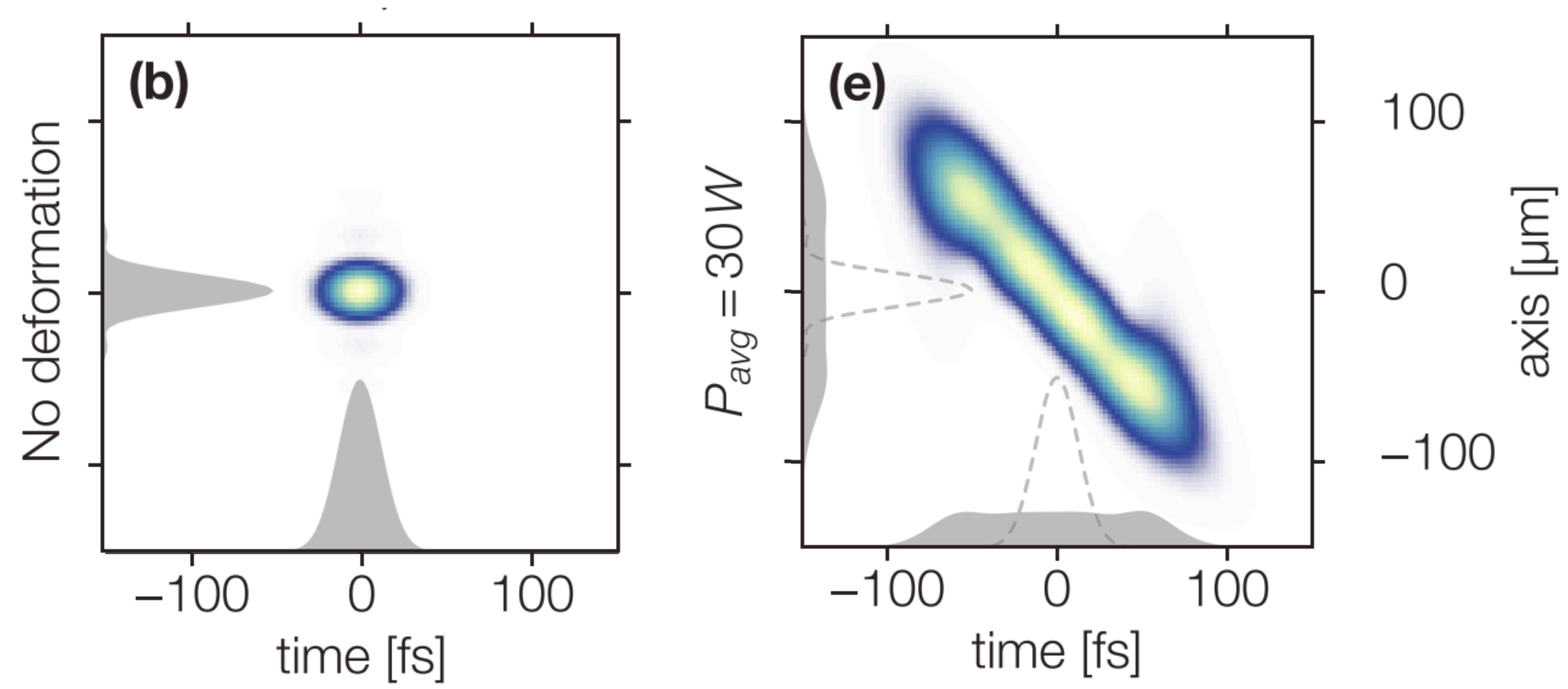
Characterisation is Key

Identification of spatiotemporal couplings can lead to use/mitigation



Continuous Monitoring

Single-shot & on-shot techniques will be essential moving forward

Closing the Loop

High-fidelity measurements and incorporation into simulations [4] will improve accuracy and provide further insight

LASY

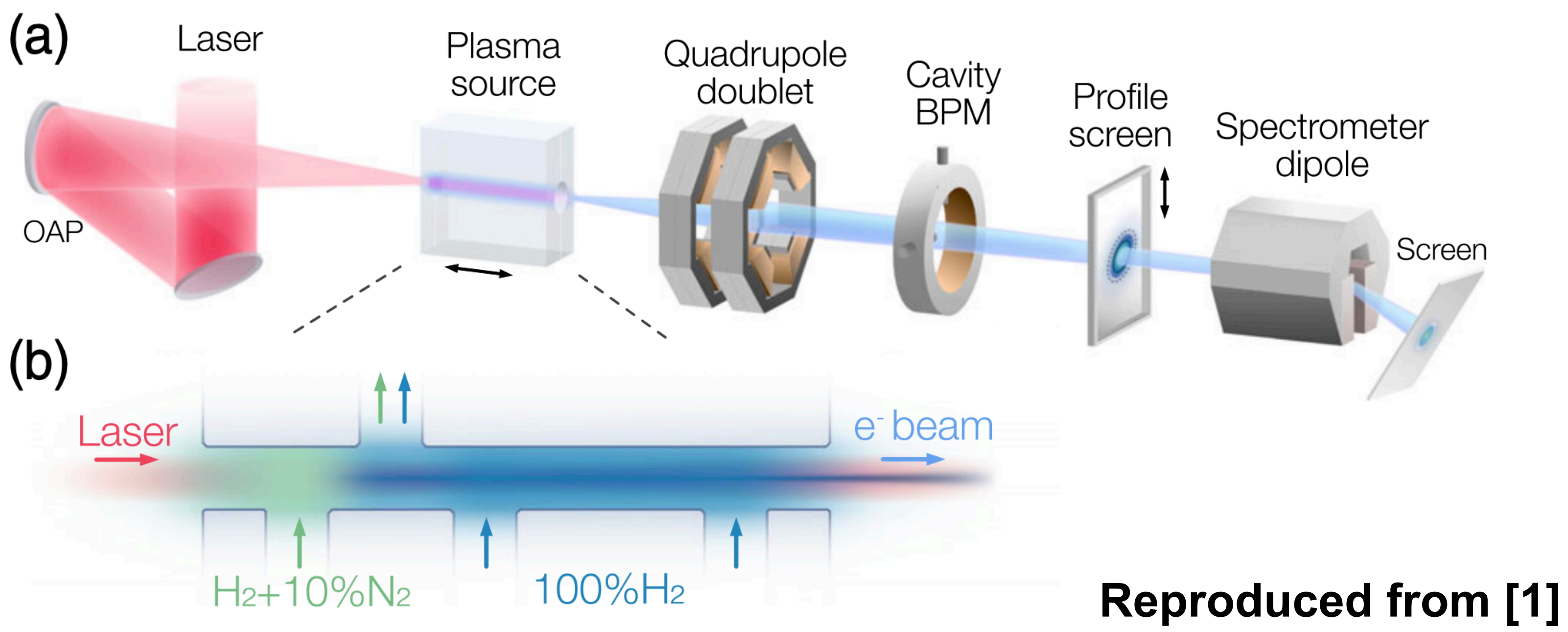
[1] M. Thévenet et al., *Phys. Rev. Accel. Beams* **22**, 071301 (2019)
[2] D. E. Mittelberger et al., *Phys. Rev. E* **100**, 063208 (2019)
[3] V. Leroux, T. Eichner & A. R. Maier, *Optics Express* **28**, 8257 (2020)
[4] https://github.com/LASY-org/lasy

Neutral Gas Source Tailoring

High-Fidelity Neutral Gas Sources with Integrated Controls and Diagnostics

The plasma source, composition and density profile is of vital importance to controlling the accelerated electron beams.

Tailoring of the plasma source is critical to both controlled injection and guiding



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Tuneability should be prioritised

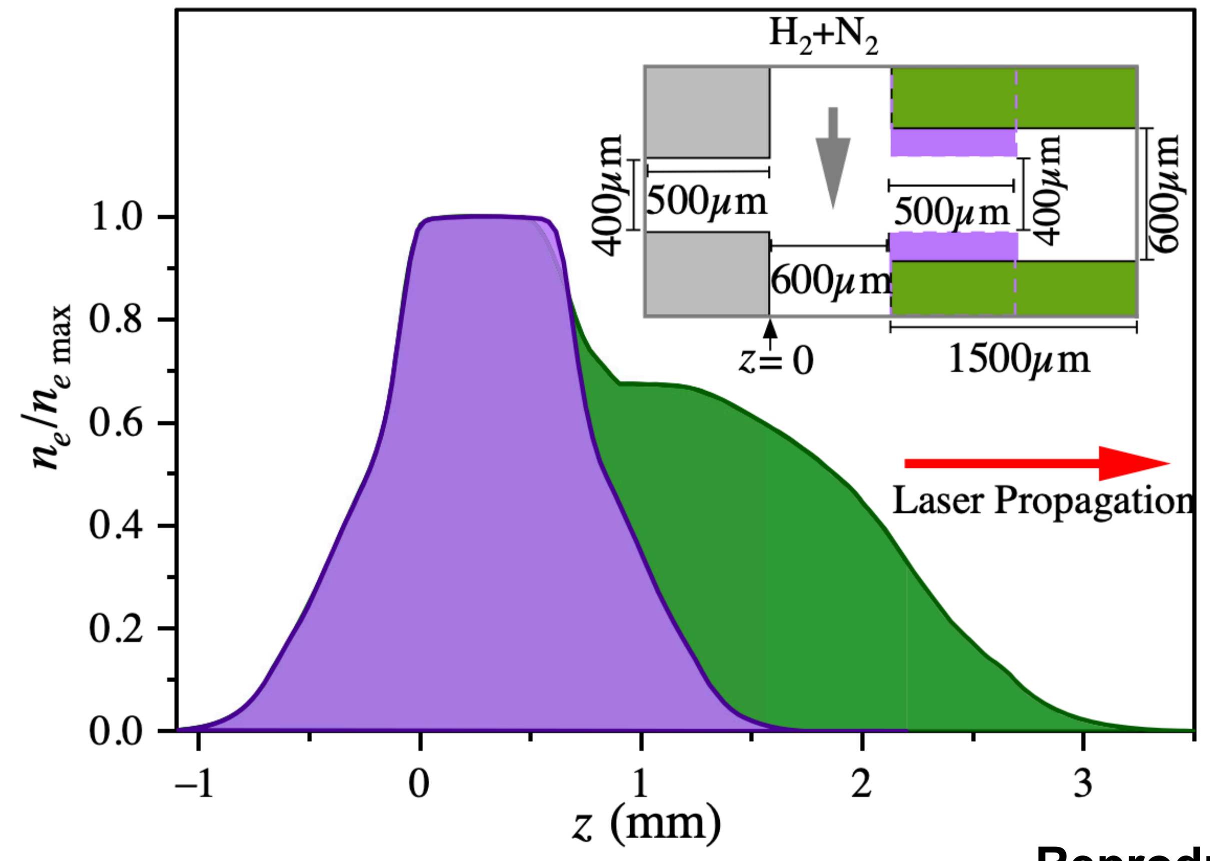
Density, ramps, plasma composition, segmenting,

Gas Flow Management

Differential pumping for reduced load on pumps, continuous flow operation

Simulations & Diagnostics

Accurate simulations of gas sources benchmarked by measurements



Reproduced from [2]

[1] M. Kirchen et al., *Phys. Rev. Lett.* **126**, 174801 (2021)
[2] L. T. Dickson et al., *Phys. Rev. Accel. Beams* **25**, 101301 (2022)

Beam Extraction and Manipulation

Development of key compose

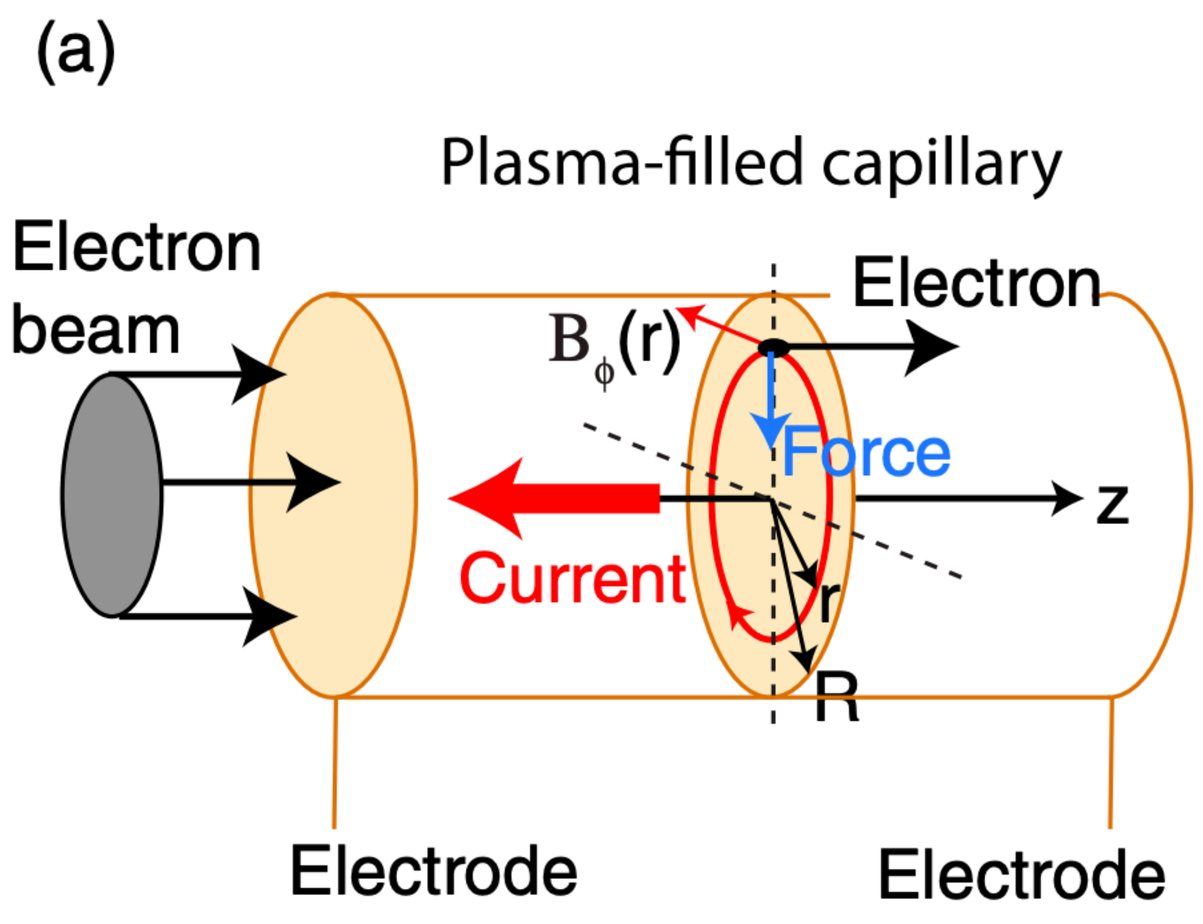
Careful extraction of both the laser and electrons are important for machine safety and for delivering high-quality beams for applications

Plasma accelerated electron beams offer a unique challenge here!

Plasma-Based Accelerator Optics
Continued development of plasma lenses, dechirpers etc.

Extraction of Electron Beam
Capture of the electron beam while mitigating emittance growth

Extraction of Laser Pulse
At kW level, the laser must be appropriately extracted/dumped



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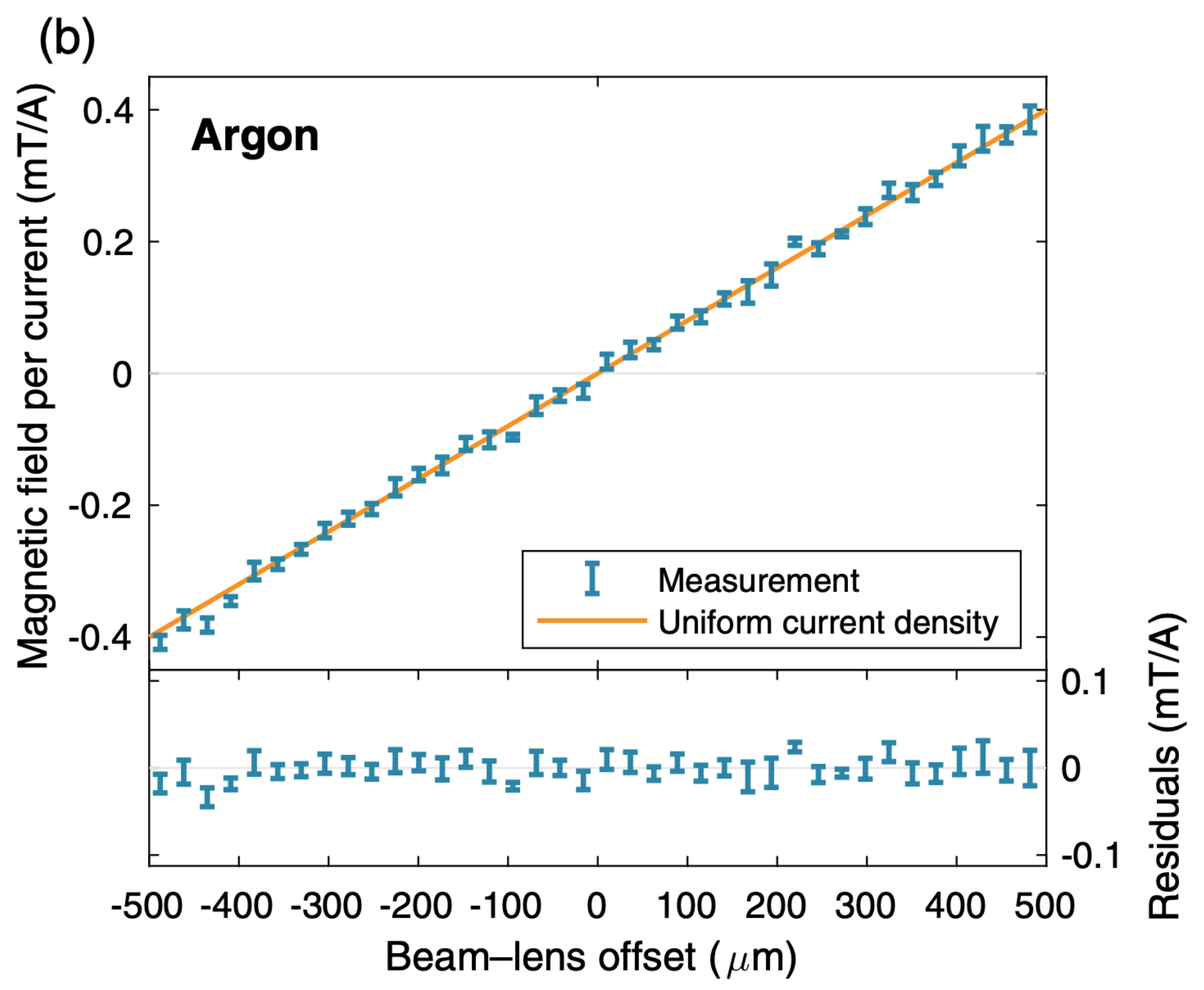


Reproduced from [2]

[1] J. van Tilborg et al., *Phys. Rev. Lett.* **115**, 184802 (2015)
[2] C. A. Lindstrøm et al., *Phys. Rev. Lett.* **121**, 194801 (2019)

Control and Stabilization Techniques

Advanced Experimental Control, Optimization and Stabilization

Control and optimization of accelerated electron beams is difficult due to coupling between input parameters and the dynamic evolution of the accelerating structure.

Machine learning techniques such as Bayesian Optimisation have demonstrated their ability to autonomously optimise the generated electron and x-ray beams from LPAs.

Improved Algorithms

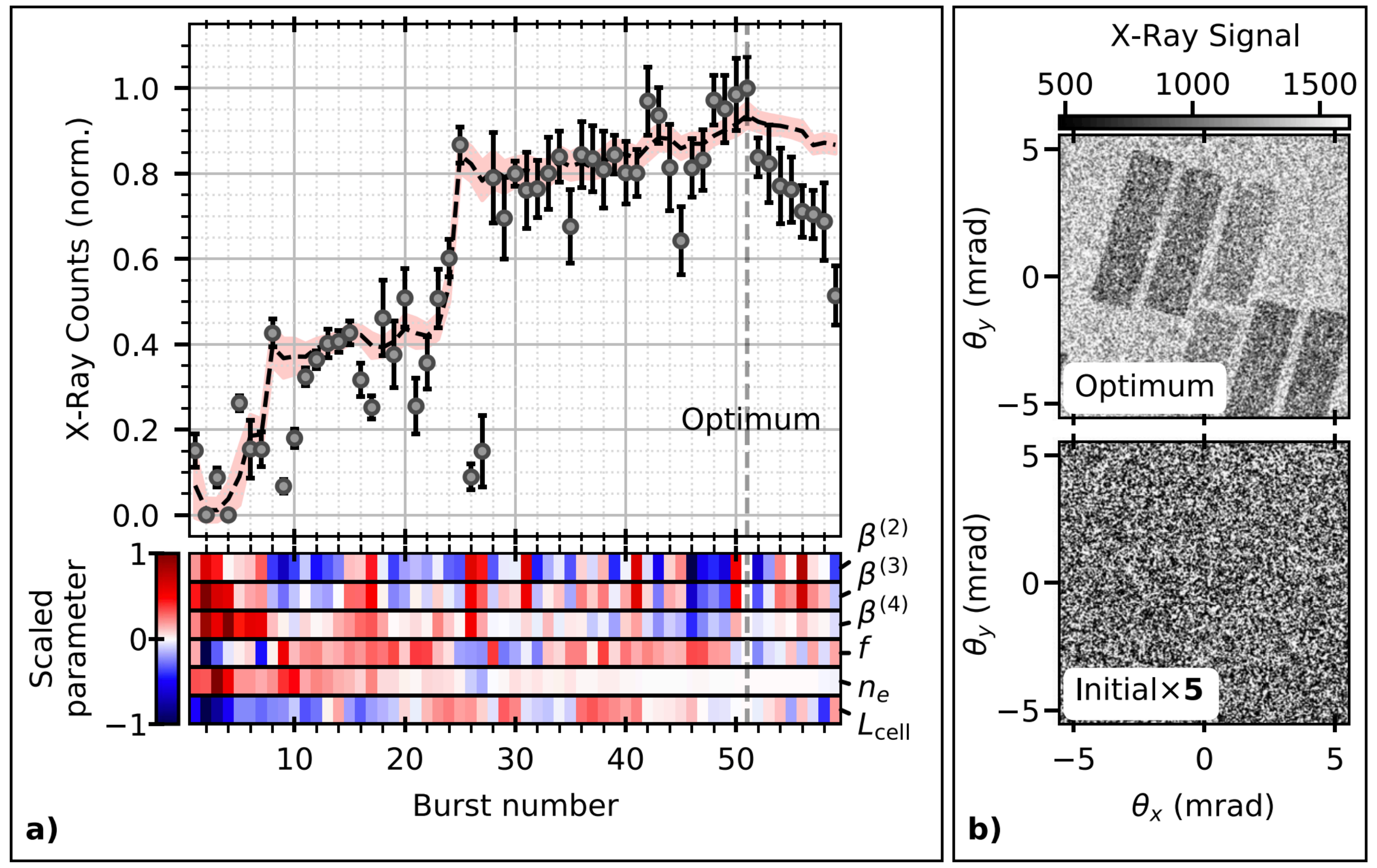
Better able to cope with experimental noise

Focus on Stability

Optimise for stable operation[2], not just best beams.

Intelligent Operation

Monitor 'health' of accelerator and identify sources of damage before they propagate



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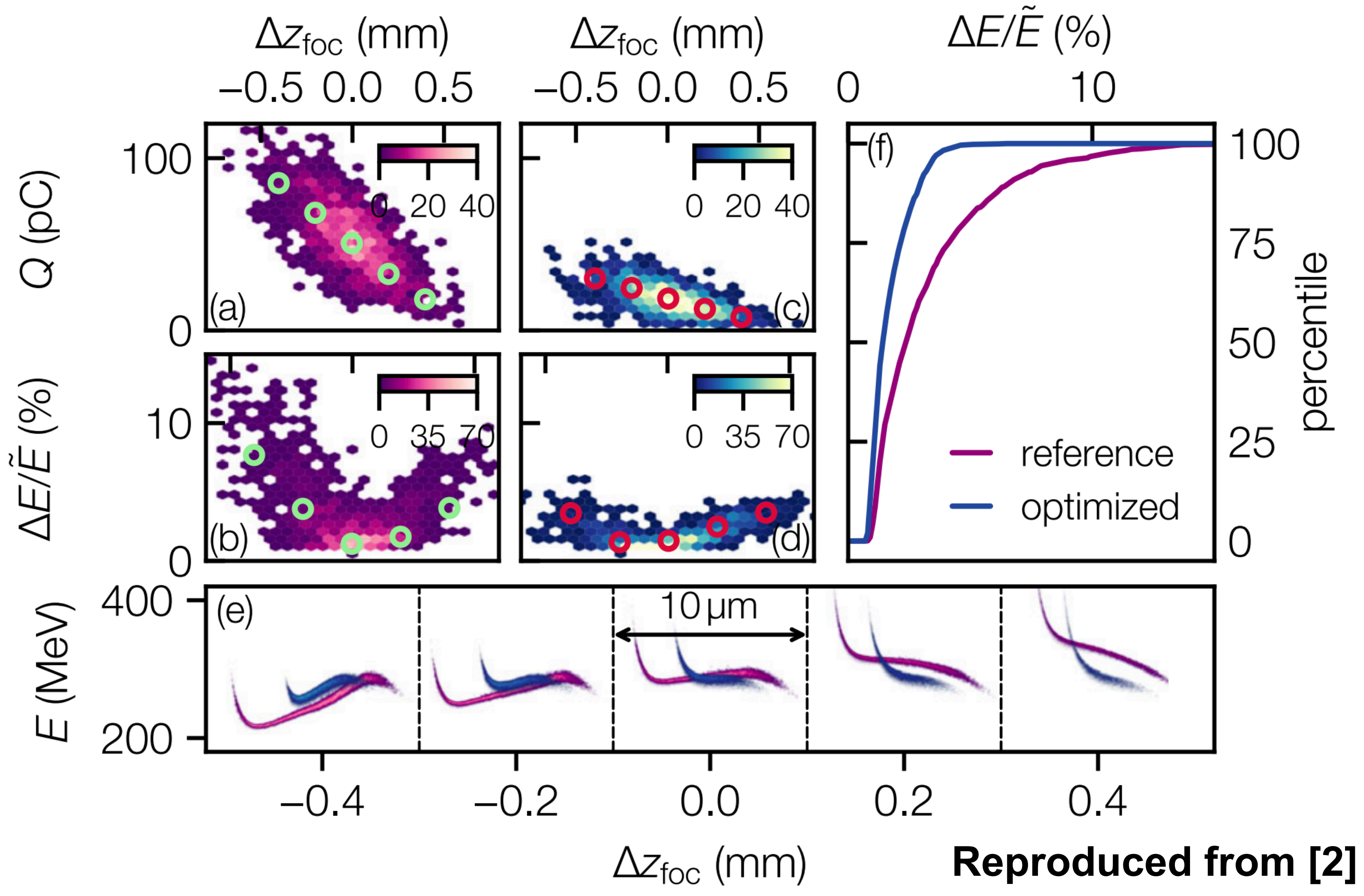

Reproduced from [2]

[1] R. J. Shalloo et al., *Nat. Comms.* **11**, 6355 (2020)
[2] S. Jalas et al., *Phys. Rev. Lett.* **126**, 104801 (2021)

Summary

Plasma-based particle accelerators for scientific and societal applications

- DESY is committed to advancing plasma as a key future accelerator technology
- A vibrant research community exists at DESY with wide ranging expertise and focus
- Our research is supported by state of the art facilities
- Several areas of potential overlap proposed

Advanced Laser Diagnostics
Measurement of spatiotemporal couplings. On-shot and dedicated diagnosis

Neutral Gas Source Tailoring
Towards developing robust plasma sources capable of supporting kHz LPA operation

Beam Extraction and Manipulation
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Thanks for your attention