X-band energy spread minimizer

Bridging the gap between plasma accelerators and synchrotron light sources

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Sören Jalas, Manuel Kirchen, Wim Leemans, Andreas Maier, Alberto Martinez de la Ossa,
Jens Osterhoff, Eva Panofski, Rob Shalloo, Maxence Thévenet, Paul Winkler and more…

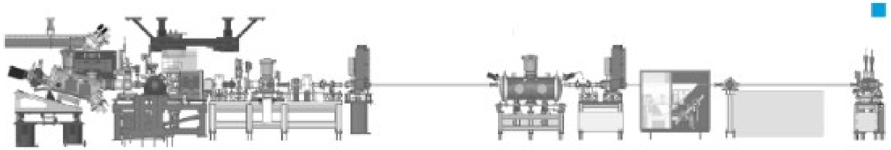
CLIC Project Meeting, CERN, May 12, 2022

HELMHOLTZ

DESY.

Roadmap for laser plasma accelerators at DESY:

FEL drivers, state-of-the-art storage ring injectors, high repetition rate photon sources, etc

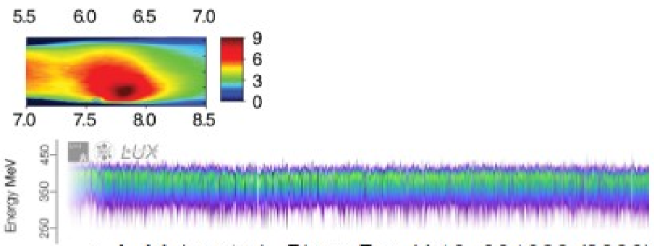


Demo-FEL operational at LUX
- Demonstrate LPA powering an FEL
- Long term runs (week or more)

Medical initiatives
- PLASMED X
- Radiation biology with ARES/PITZ and LPAs

2019

Laser plasma accelerators
- Up to 8 GeV energy
- 1% energy spread, µm emittance
- 29h stability run



→ *A. Maier et al., Phys. Rev. X 10, 031039 (2020)*

2021

CDR for PETRA IV injection
- design study for a 6 GeV plasma injector

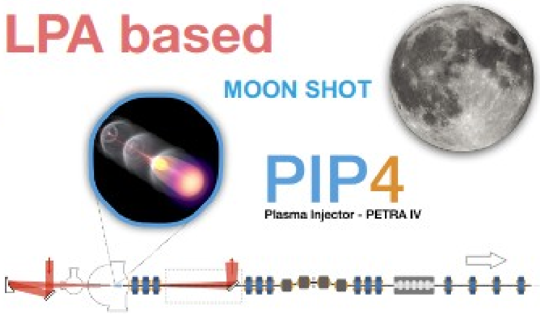
2023

kHz X-ray source and kHz FEL
- KALDERA drives novel sources

KALDERA operational
- Multi-kW laser
- kHz operation of LPA
- Feedback/ML control
- Long term stability runs

2025+

2nd injection system R&D for PETRA IV: LPA based



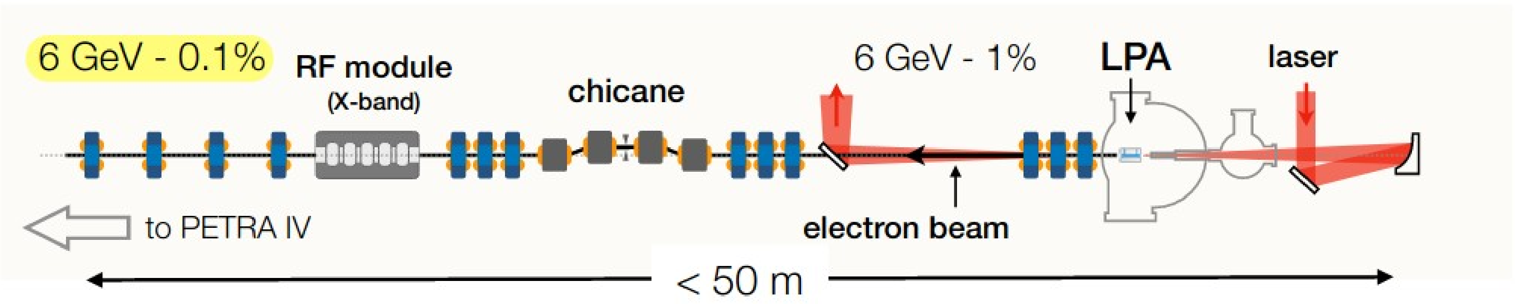
The moonshot: LPA plasma injector for PETRA IV

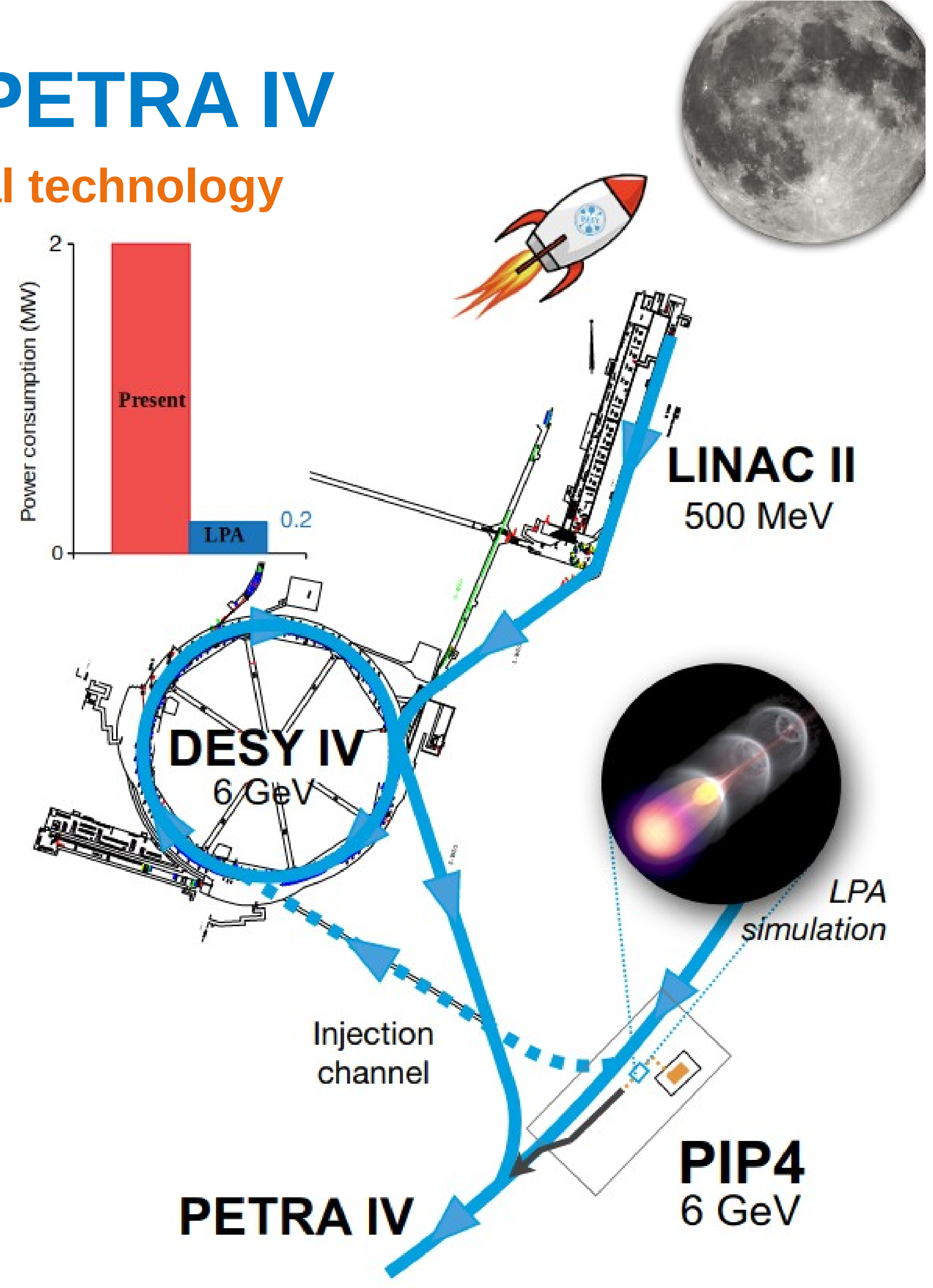
Competitive, compact, and cost-effective alternative to conventional technology

Enabling laser plasma accelerators (LPAs) for top applications

- Builds upon successful LPA development at DESY (LUX) for enhanced beam quality, reliability and performance (24/7).
- Active feedback with AI control for enhanced stability (KALDERA).
- New laser guiding technologies for efficient 6 GeV energy gain.
- State-of-the-art computing capabilities for precise modeling and advanced machine learning optimization.
- Novel conceptual beamline, enabling per-mille levels of energy bandwidth and stability.

plasma injector beamline schematic





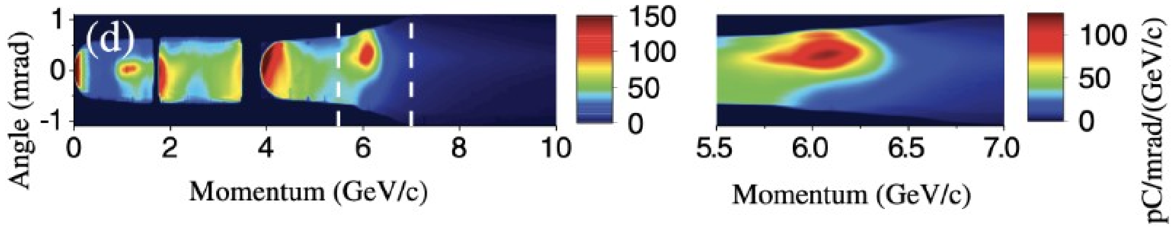
What is possible Today for Laser-Plasma Accelerators?

6 GeV energy and 1-2 % energy spread and stability (but not simultaneously)

BELLA@LBNL: multi-GeV acceleration

- Guiding of intense petawatt-class lasers:
  62 pC at 6 GeV has been demonstrated
- Research led by Wim Leemans (now at DESY)

→ *A. J. Gonsalves et al. Phys. Rev. Lett. 122, 084801 (2019)*



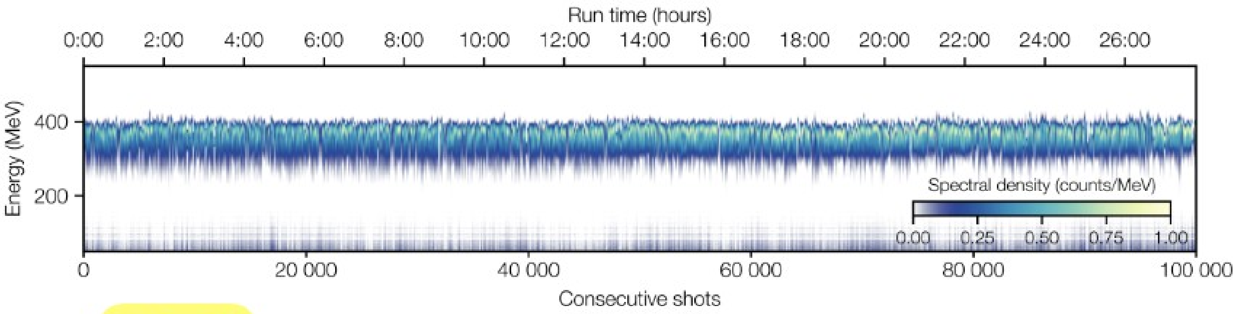
LUX@DESY: enhanced energy spread and stability

- Energy spread optimization: 1.1% (mad)
- 24-hour run: 100 000 consecutive electron beams
- Prospects of enhanced control and stability through active feedback powered by AI.

1% beam energy spread and stability can be expected with moderate improvements on the laser side

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

→ A. Maier et al., Phys. Rev. X 10, 031039 (2020)



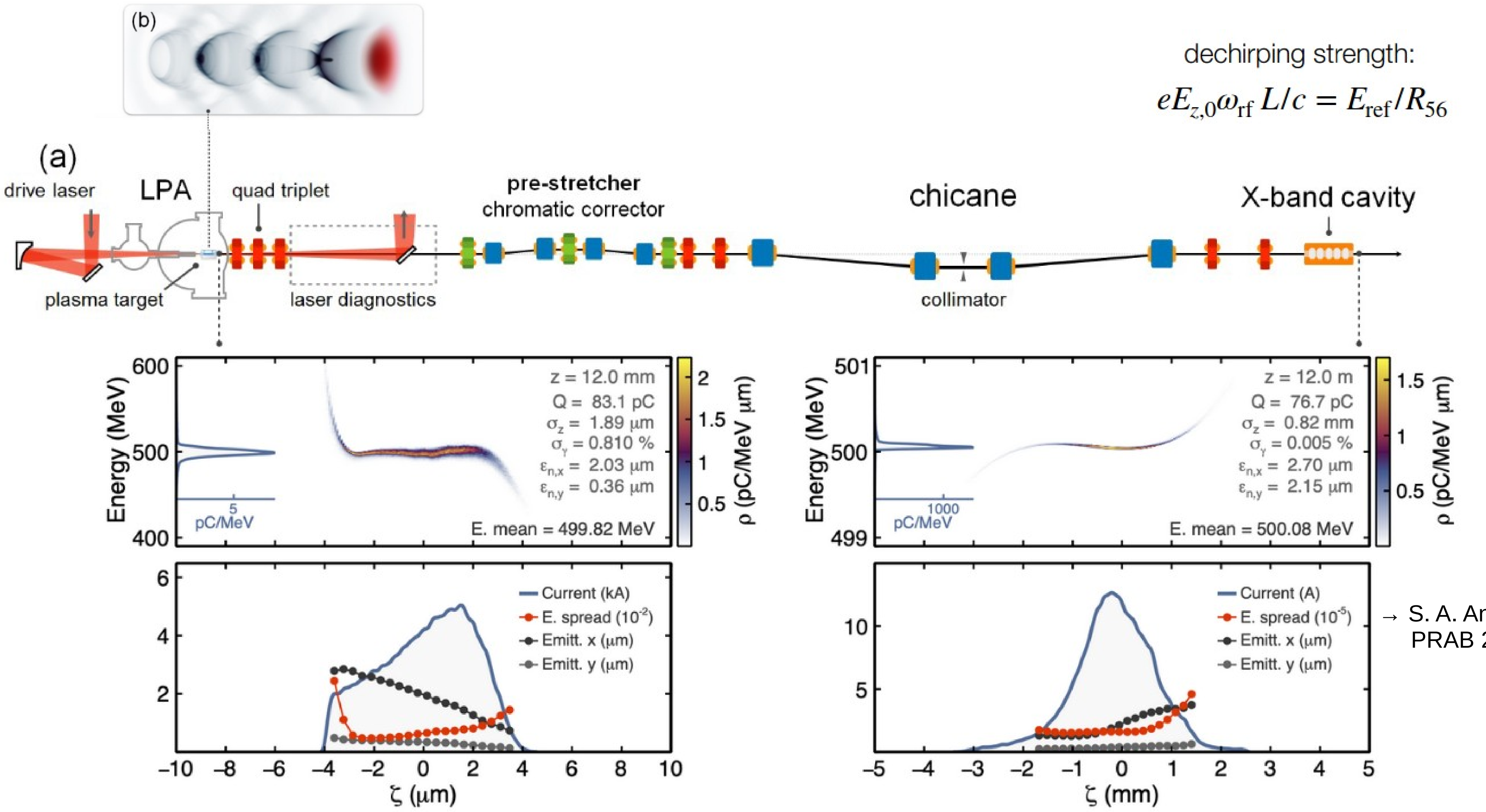
1.8 % energy jitter

Prototype laser-plasma injector for an electron synchrotron

Sub-per-mille energy spread and stability for future storage rings

dechirping strength:

$$eE_{z,0}\omega_{\mathrm{rf}}\,L/c = E_{\mathrm{ref}}/R_{56}$$



→ S. A. Antipov et al. PRAB 24, 111301 (2021)

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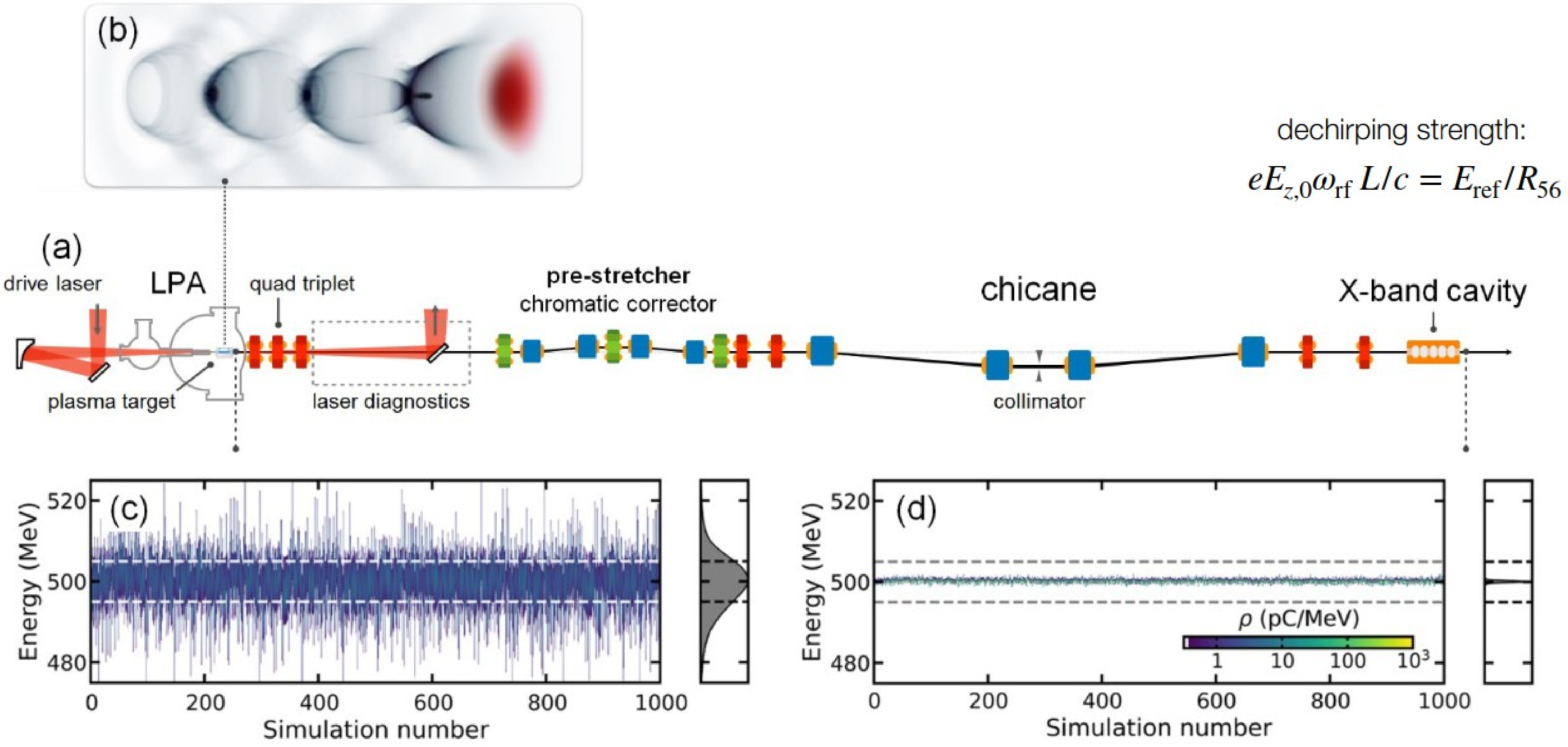

→ S. A. Antipov et al. Phys. Rev. Accel. Beams 24, 111301 (2021)

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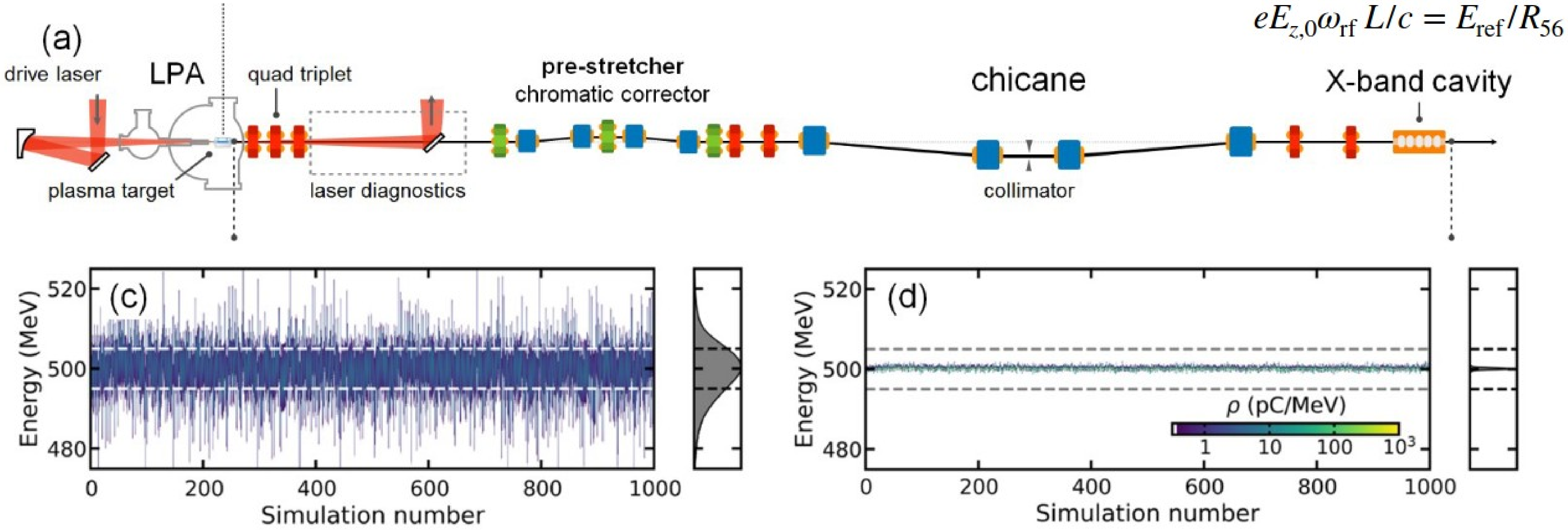


- LUX LPA optimized for lowest energy spread (0.8 %) beams at 500 MeV by means of PIC simulations with FBPIC.
- Beamline simulations (R_{56} = 10 cm, 12 GHz) show a reduction of the relative energy spread down to 0.005%.
- Statistics of 1000 bunches with 1% energy jitter exhibits a **final beam energy distribution with 0.04% rms**.
- Bunches become 430 times longer (6 ps FWHM): suitable for injection in storage ring.

Can implement a staged approach

Goal: demonstrate record energy spread, stability of LPA beam

1. Demonstrate energy compression with X-Band RF using the existing LUX beamline with minimal modifications

   available *can be built* *missing*

   - Need: LPA, capture quads, chicane, diagnostics, RF system, Laser-2-RF sync, X-band cavity
   - Can be done in 1-2 years

2. Demonstrate injection into DESY-II at 450-500 MeV using the ANGUS laser

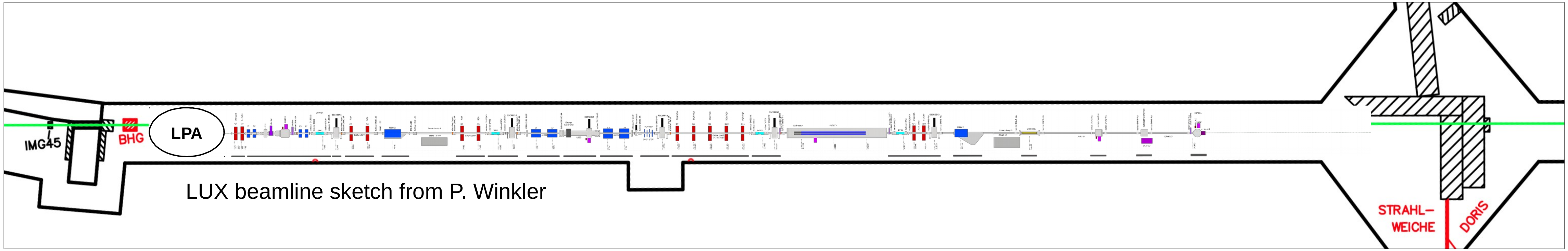
   - Completely new beamline has to be built (some hardware might be reused)
   - Alternatively, use the PIA ring as a bypass (option needs further investigation)

3. … Build a full-scale 6 GeV injector

   - Need research on the plasma cell

Step 1: Proof-of-principle prototype at LUX

Goal: demonstrate record energy spread, stability of LPA beam



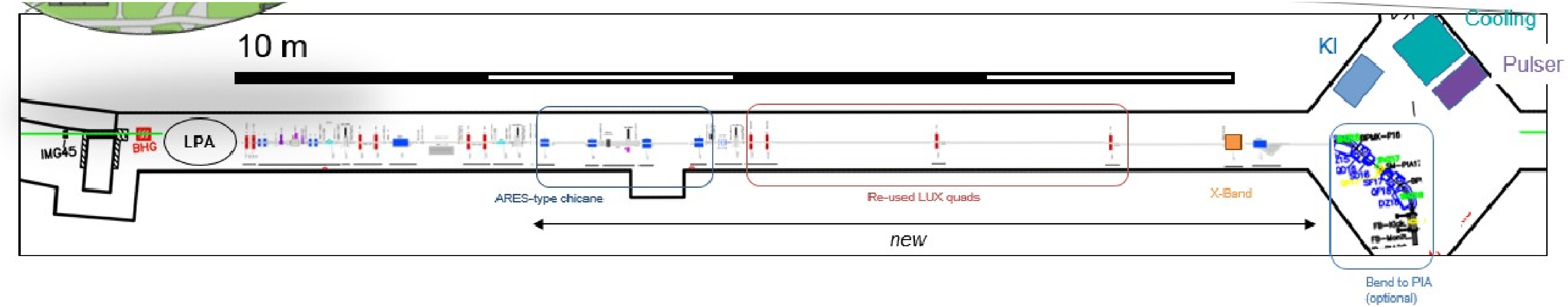
LUX beamline sketch from P. Winkler

Existing LUX beamline

- 500 MeV range LPA FEL demostrator
- Record (for an LPA) 24-h-long continuous run
- A lot of beam diagnostics

Step 1: Proof-of-principle prototype at LUX

Goal: demonstrate record energy spread, stability of LPA beam



Test bench for longitudinal phase space manipulation

- Highly relevant research towards improving quality, stability, staging of LPAs.
- Re-using existing hardware and infrastructure
- Can be done in about 2 years

Beam energy	350-500 MeV
Bunch charge	~ tens pC
Initial energy variation	~ 1%
Repetition rate	~1 Hz
Capture quads	< 100 T/m
Chicane	R_{56} = 5-10 cm
RF	**10-12 GHz, V < 25 MV**
Laser-rf-synch	~100 fs rms
Final energy variation	< 0.1%
Final norm. emit	~ 1 μm

Step 1: Proof-of-principle prototype at LUX

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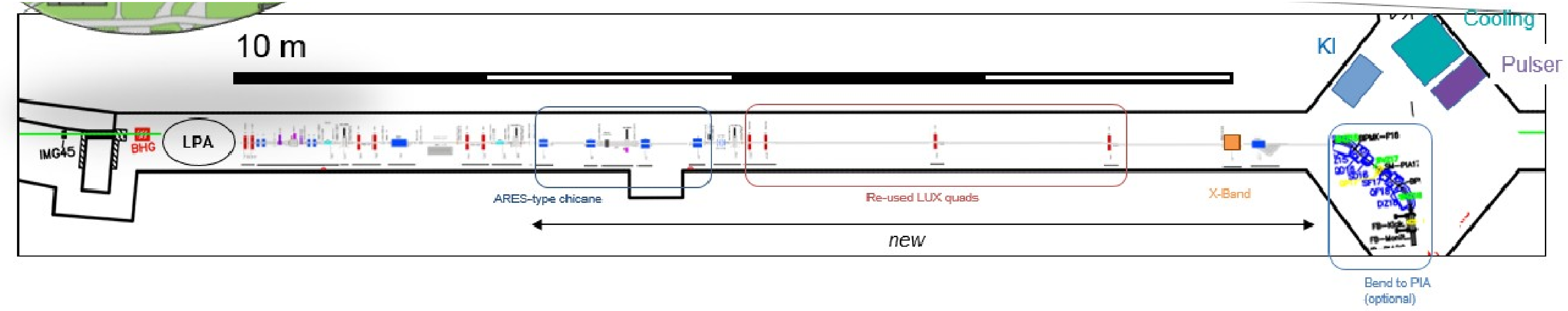
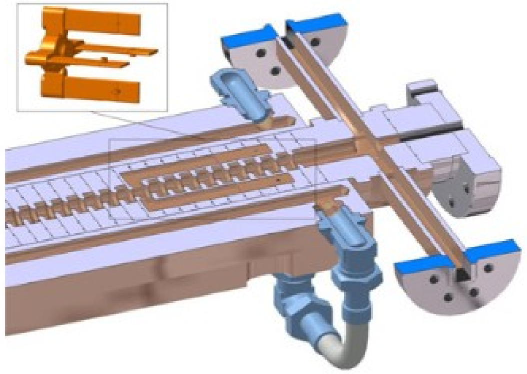


CERN X-Band seems an ideal choice

- Proven technology → L.S. Cowie et al., IPAC'18
- 30 MV/m with a 6 MW X-Band RF system identical to FLASH TDS
- Aperture scraping, transverse wakes not an issue
- System can be scaled up to 6 GeV

CERN/PSI X-band structure



X-Band RF can help LPAs achieve unprecedented levels of energy spread and stability

Crucial for practical applications such as injectors for future light sources

A proof-of-principle demonstrator is within reach

- Only already existing infrastructure and technology
- Building up on the operational expertise of the LUX LPA

Present state

- Looking into the technical sub-systems, layout, and integration
- Preparing a realistic schedule, aligned with other studies and activities

Future

- Looking forward to collaborating with our CERN colleagues on this project

Thank you

Contact

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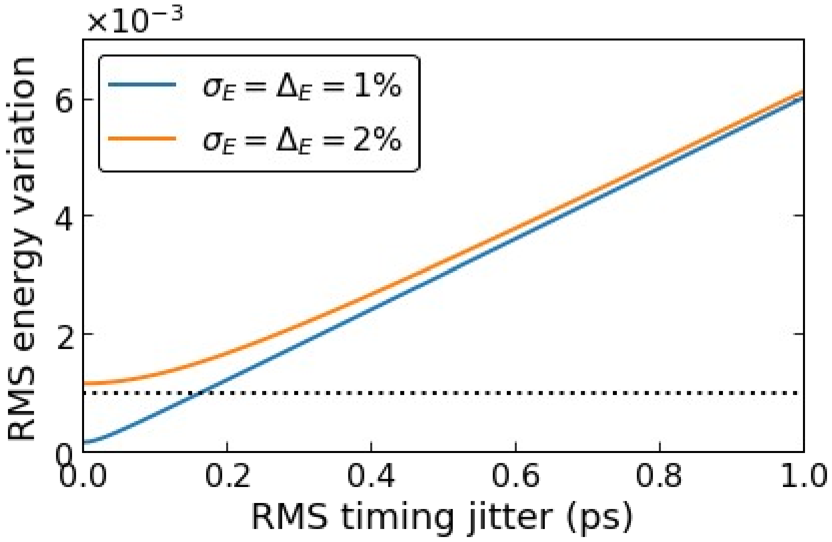
Phone

Laser-to-RF synch: Can tolerate 100 fs rms timing jitter

Achievable with RF synchronization

Sources of final energy variation:

- Initial bunch length
- Nonlinearity of RF
- RF phase and voltage errors
- LPA energy jitter
- Timing jitter

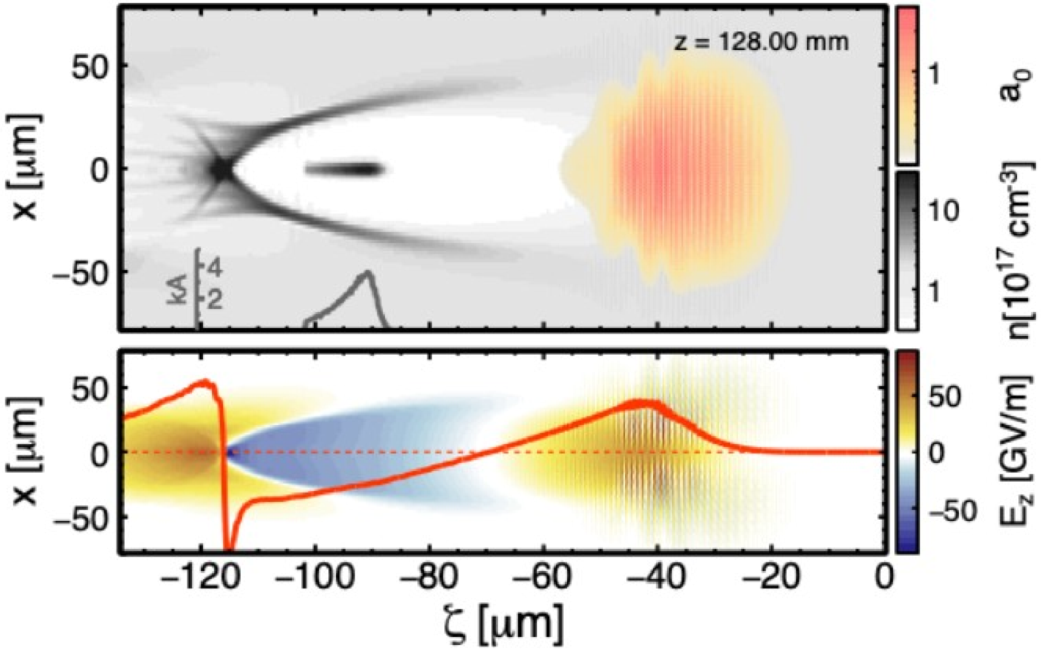


PIP4 @ DESY: 6 GeV with per-mille spread and jitter

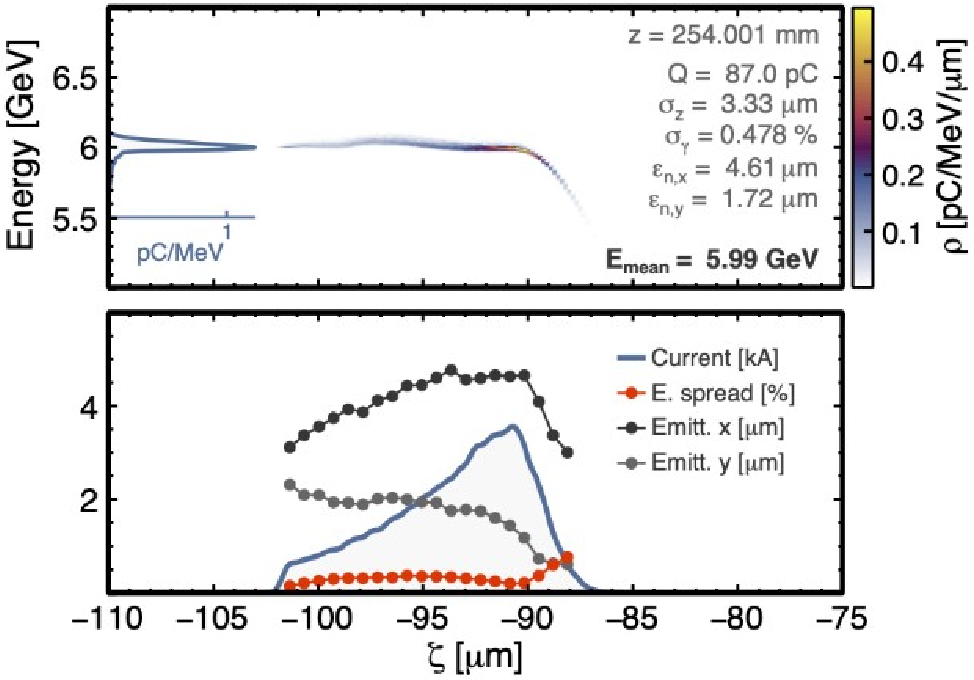
Simulated working point combining LUX approach with ideal guiding channels

Simulation studies with bayesian optimization → S. Jalas et al., Phys. Rev. Lett. 126, 104801 (2021)

- Upscaled LUX-type setup with ideal laser guiding channels
- Optimize for best quality beams at 6 GeV with minimal laser energy



Laser energy: 19 J Peak power: 345 TW



87 pC at 6 GeV with 0.5% energy spread