Energy compressor for PWA injector for PETRA IV

Bridging the gap between plasma accelerators and synchrotron light sources

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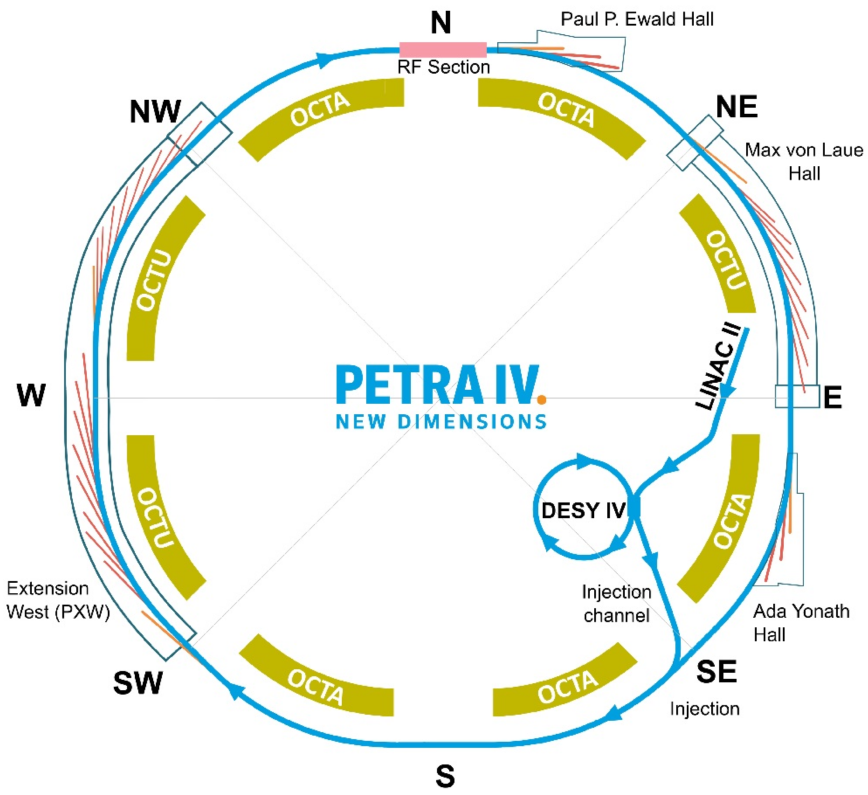
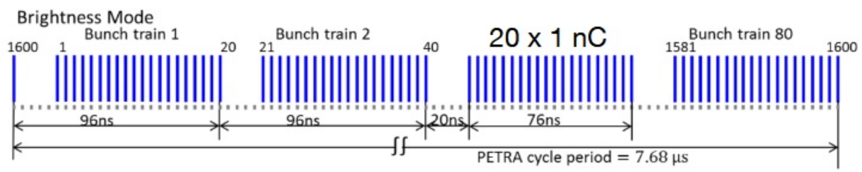
HELMHOLTZ

DESY.

The moonshot: LPA plasma injector for PETRA IV

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





To compensate for beam losses and keep bunch-to-bunch charge variation within 10% need to top-up 100 pC at 0.5 Hz

Energy	6 GeV
Circumference	2304 m
Lattice	Hybrid 6-BA
Hor. emittance	20 pm
Beam current	200 mA
Beam lifetime	10 h
Injection sheme	Off-axis accum.

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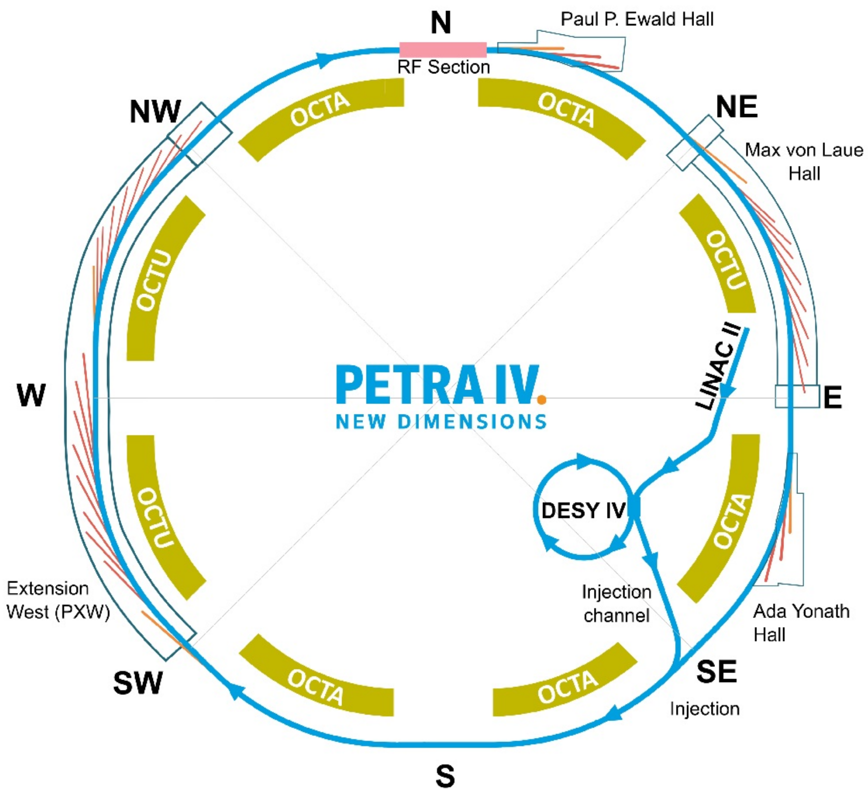


- Building upon successful LPA development at DESY (LUX) for enhanced beam quality, reliability and performance (24/7).
- Active feedback with AI control for enhanced stability (KALDERA).
- New laser guiding technologies for efficient 6 GeV energy gain.
- State-of-the-art computing capabilities for precise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

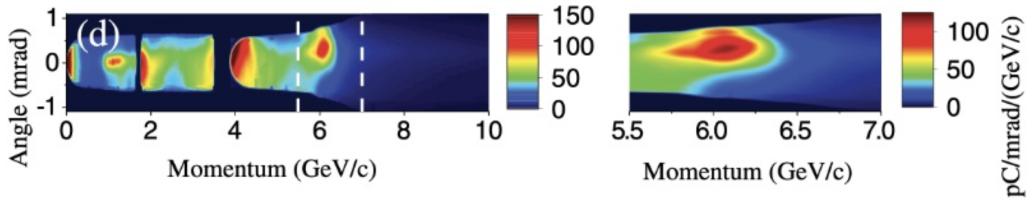
What is possible Today for Laser-Plasma Accelerators?

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

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

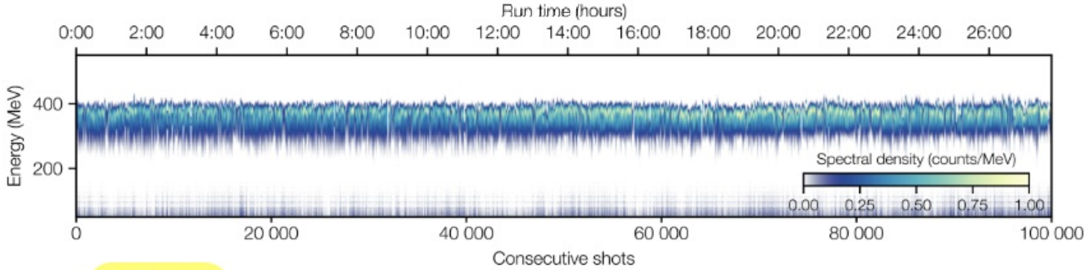


LUX@DESY: enhanced energy spread and stability

- 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.

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

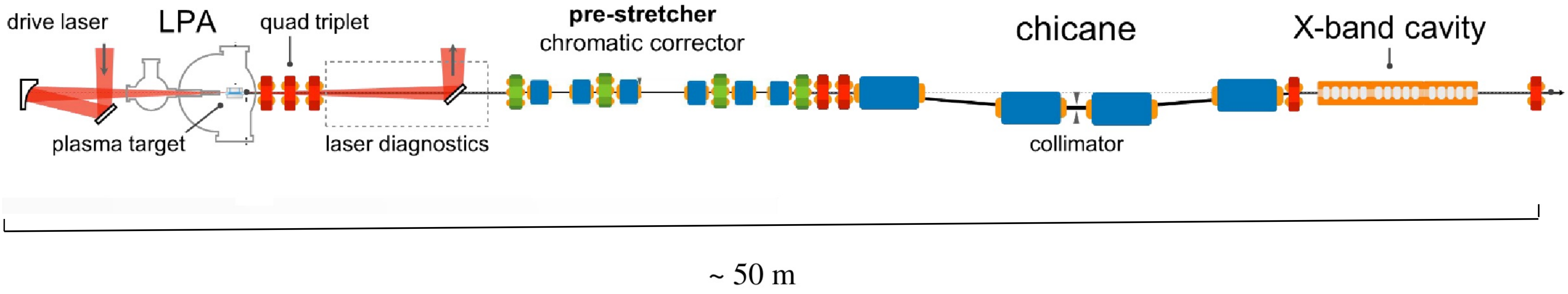
→ A. Maier et al., Phys. Rev. X 10, 031039 (2020)



1.8 % energy jitter

6 GeV beamline with X-band energy compression

Combining working, proven solutions



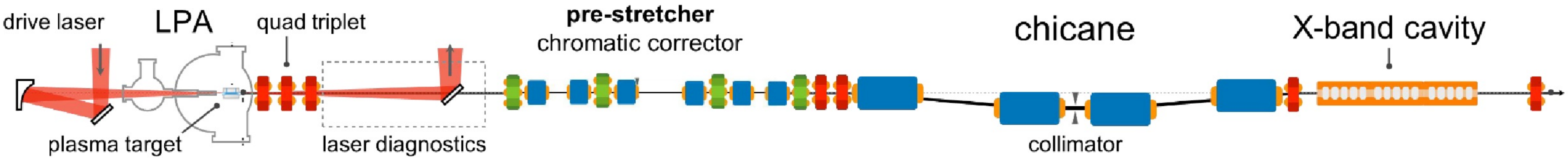
Capture triplet	50 cm, max G = 80 T/m
Pre-stretcher	R_{56} = 5 mm
Chrom. Sextupoles	30 cm, max S = 550 T/m^2
Main chicane	R_{56} = 10 cm, B = 1.45 T
Energy compressor	5 m, 12 GHz, 250 MV

→ ESRF-EBS Quads
G. Le Bec et al., PRAB 19, 5 052401 (2016)

→ CompactLight, 50 MW RF
W. Wuensch, XLS-Rep.-2021-004 (2021)

Three-stage numerical tracking

Laser to the storage ring



FBPIC

- Laser-plasma interaction
- Wakefields
- Beam loading
- Plasma density downramp assisted ionization injection

Ocelot

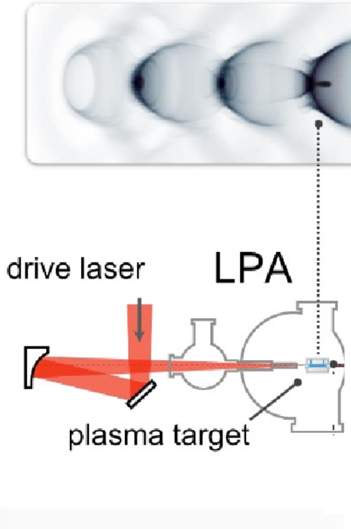
- Transport
- RF
- CSR
- Collimation

Elegant

- Lattice errors
- 3^{rd} harmonic RF
- Synch rad. damping
- Physical aperture

6 GeV LPA injector: the LPA

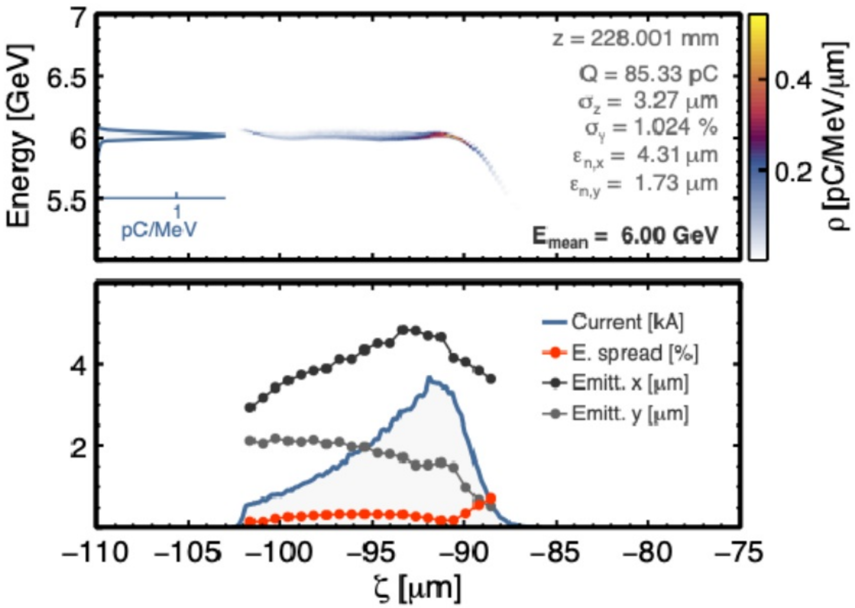
Achieving ~100 pC bunch charge within a small phase space volume

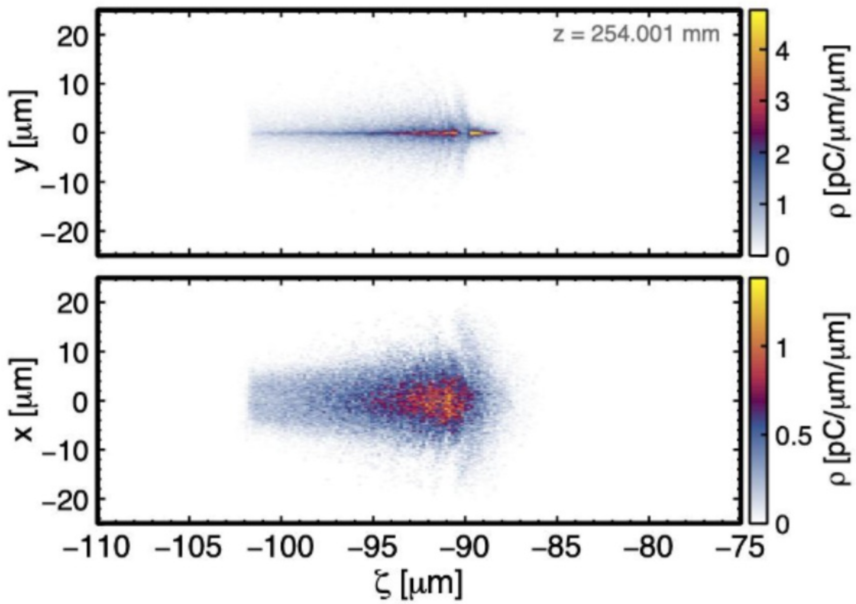


A single 25-cm-long LPA stage

Driven by a ~20 J laser pulse

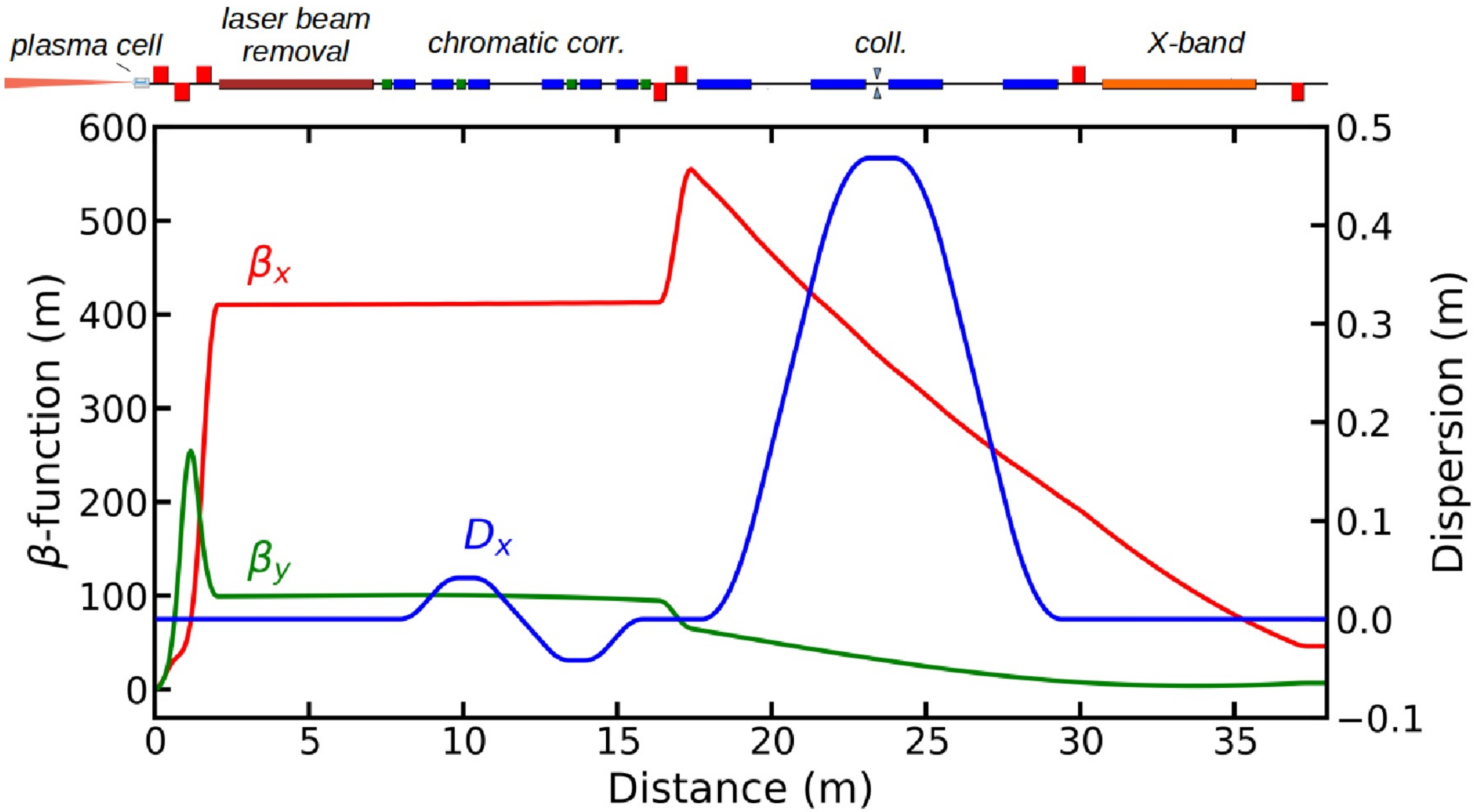
Bayesian optimization of the working point → S. Jalas et al., Phys. Rev. Lett. 126, 104801 (2021)





6 GeV LPA injector: the beamline

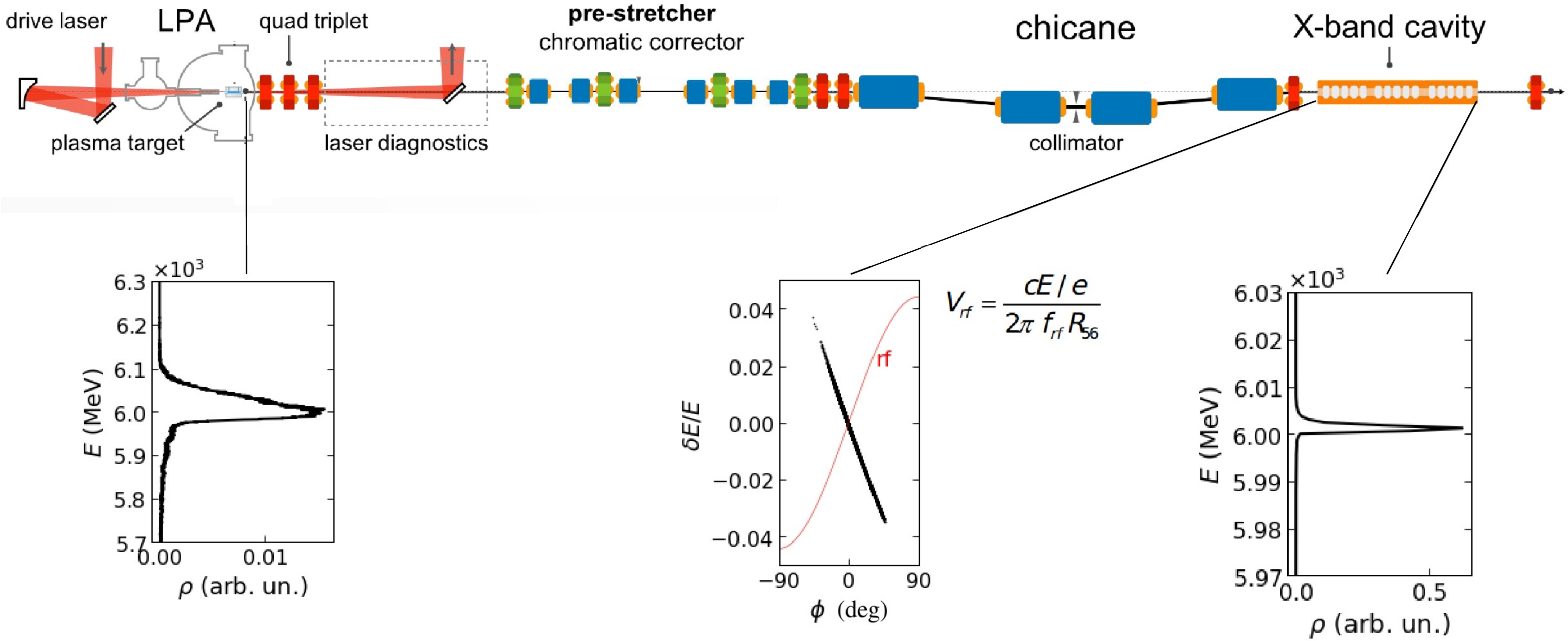
Beam capture, chromatic correction, energy compensation



→ S. A. Antipov et al., IPAC'22

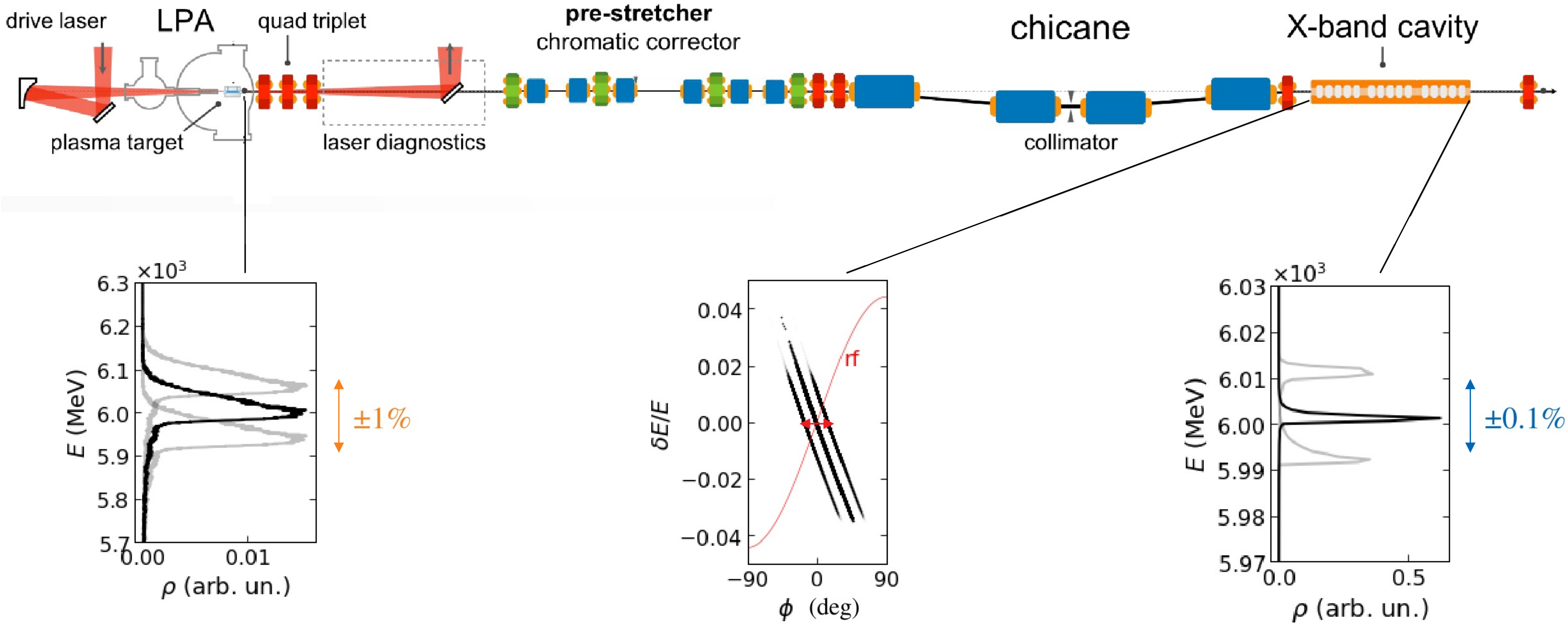
LPA energy spread correction

Improving the energy spread to sub-per-mille levels



LPA energy spread correction

Achieving per-mille energy stability



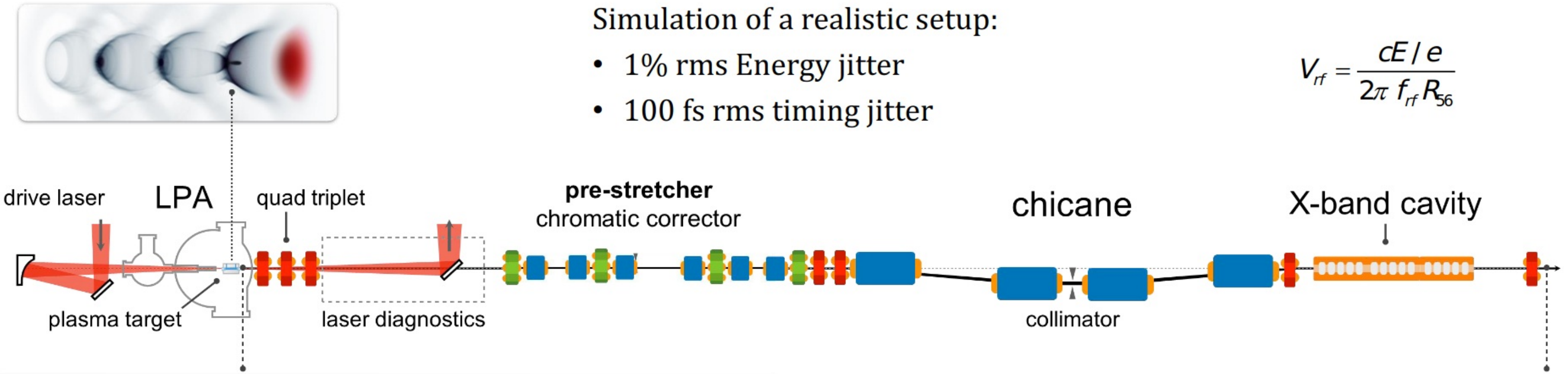
6 GeV LPA performance

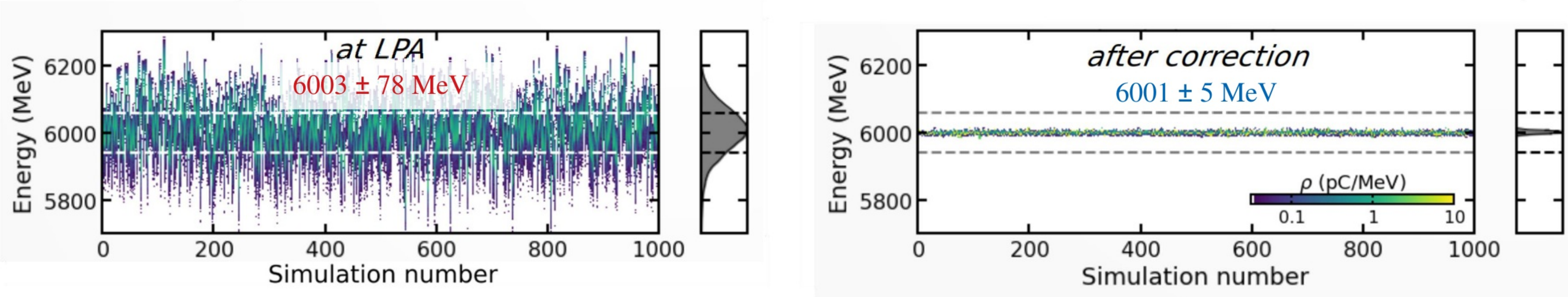
Sub-per-mille energy spread and stability for future storage rings

Simulation of a realistic setup:

- 1% rms Energy jitter
- 100 fs rms timing jitter

$$V_{rf} = \frac{cE/e}{2\pi f_{rf} R_{56}}$$





Beam quality sufficient for nearly 100% injection efficiency

Including pointing angle errors

Final emittance – about **1 nm-rad**

Assuming a realistic laser pointing angle fluctuation (rms fluctuation = rms divergence)

For comparison, DESY-IV will provide 19, 2 nm-rad

Start-to-end injection efficiency simulation:

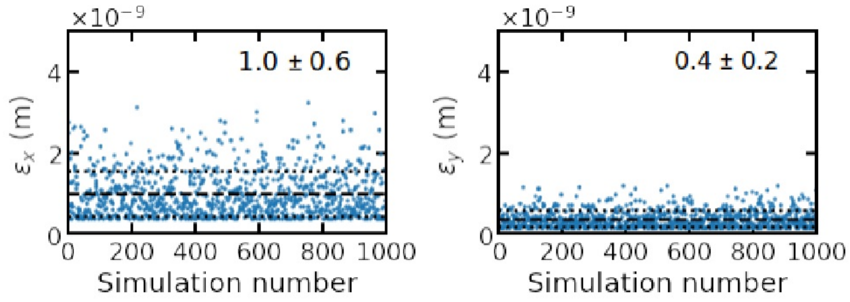
Element-by-element simulation in ELEGANT

Realistic 5% b-beating

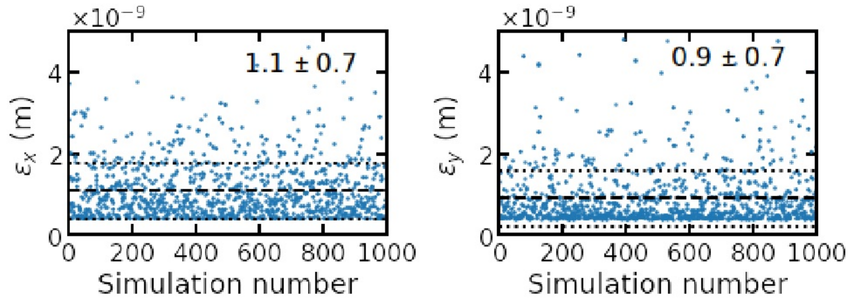
Simulated 20 machines, small losses in 1 case

No beam rotation or aperture sharing required

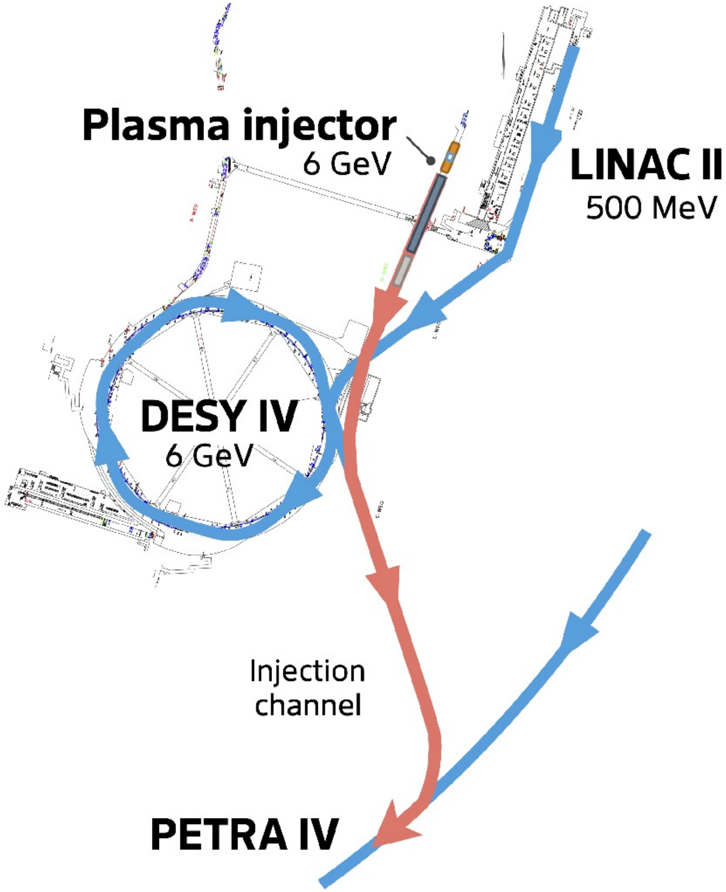
- Before capture



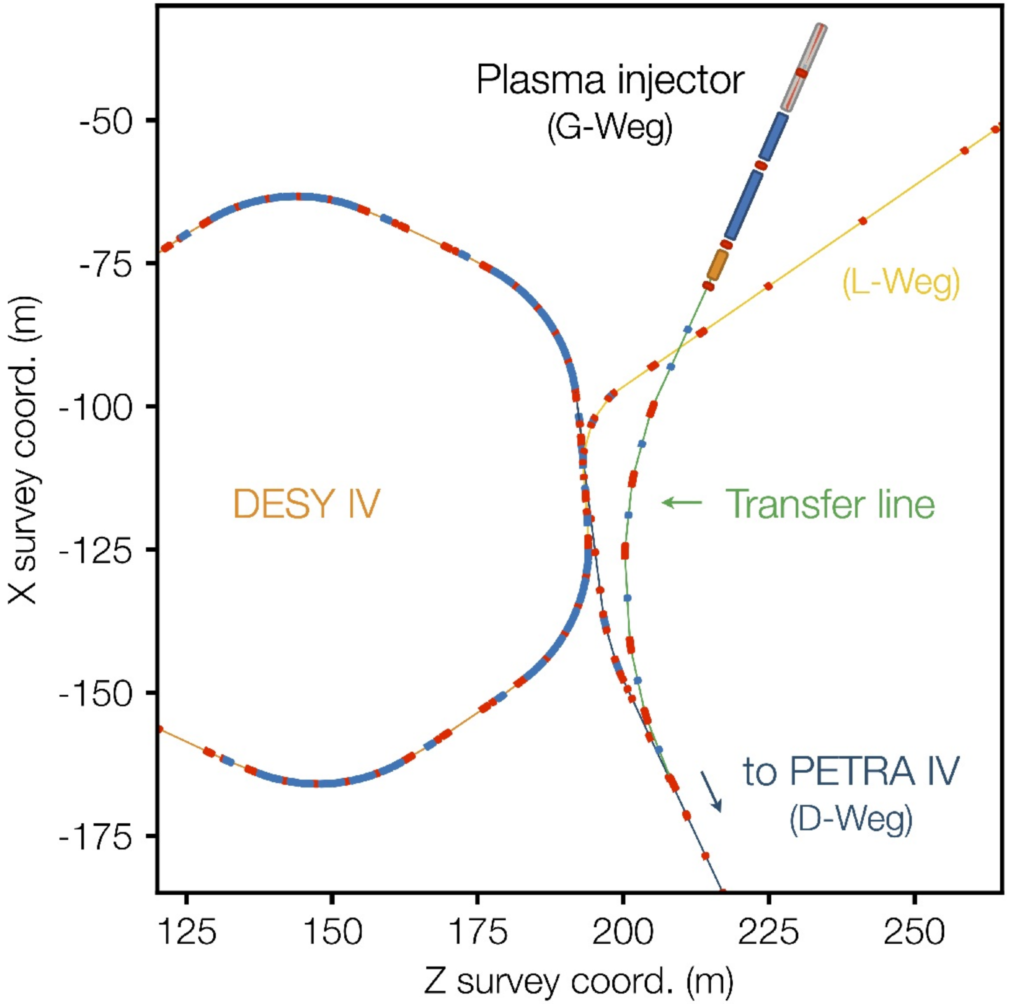
- At the exit of the beamline



Potential layout



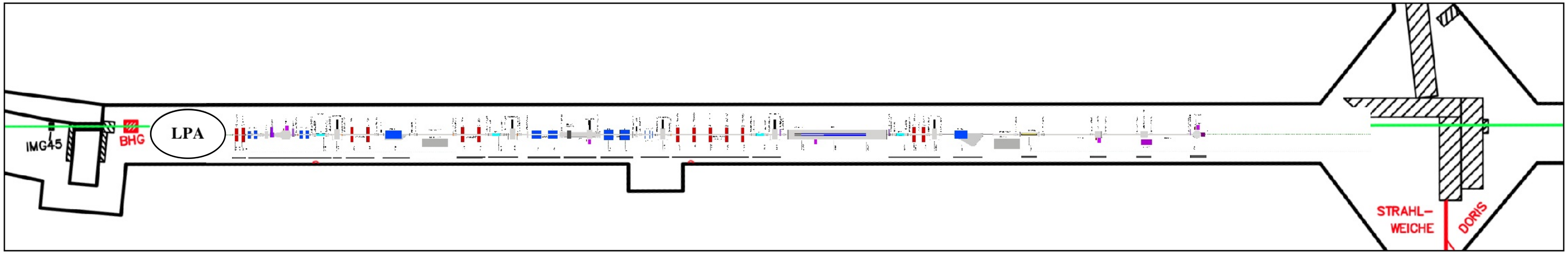
Courtesy A. de la Ossa



Step 1: Proof-of-principle prototype at LUX

Goal: **demonstrate record energy spread, stability of LPA beam**

Timeline: **two years**



Courtesy P. Winkler

Existing LUX beamline

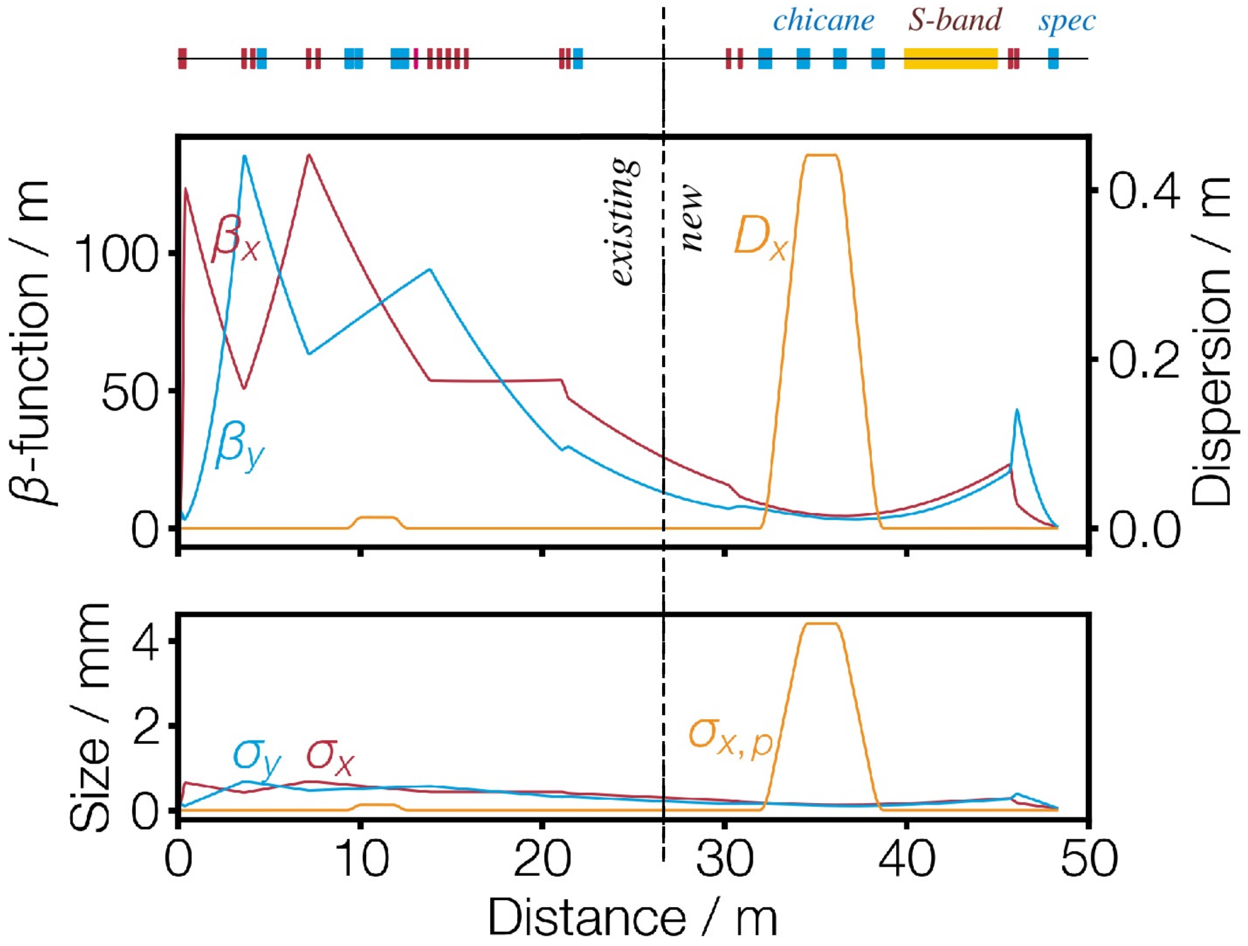
- 500 MeV range LPA FEL demostrator
- Record 24-h-long continuous run
- Screens and spectrometers for diagnostics

Separate LUX optics for the prototype test

Weaker focusing, large momentum acceptance

Magnet positions left intact

- Drastically lower chromaticity: (-30, -8) vs (-105, -84)
- Only half the quadrupoles used
- Adding a 12 deg chicane, R56 ~ 15-20 cm
- **Beam size** at **RF** cavity **< 1 mm**
- Final **beam size** at **e-spec < 0.1 mm**

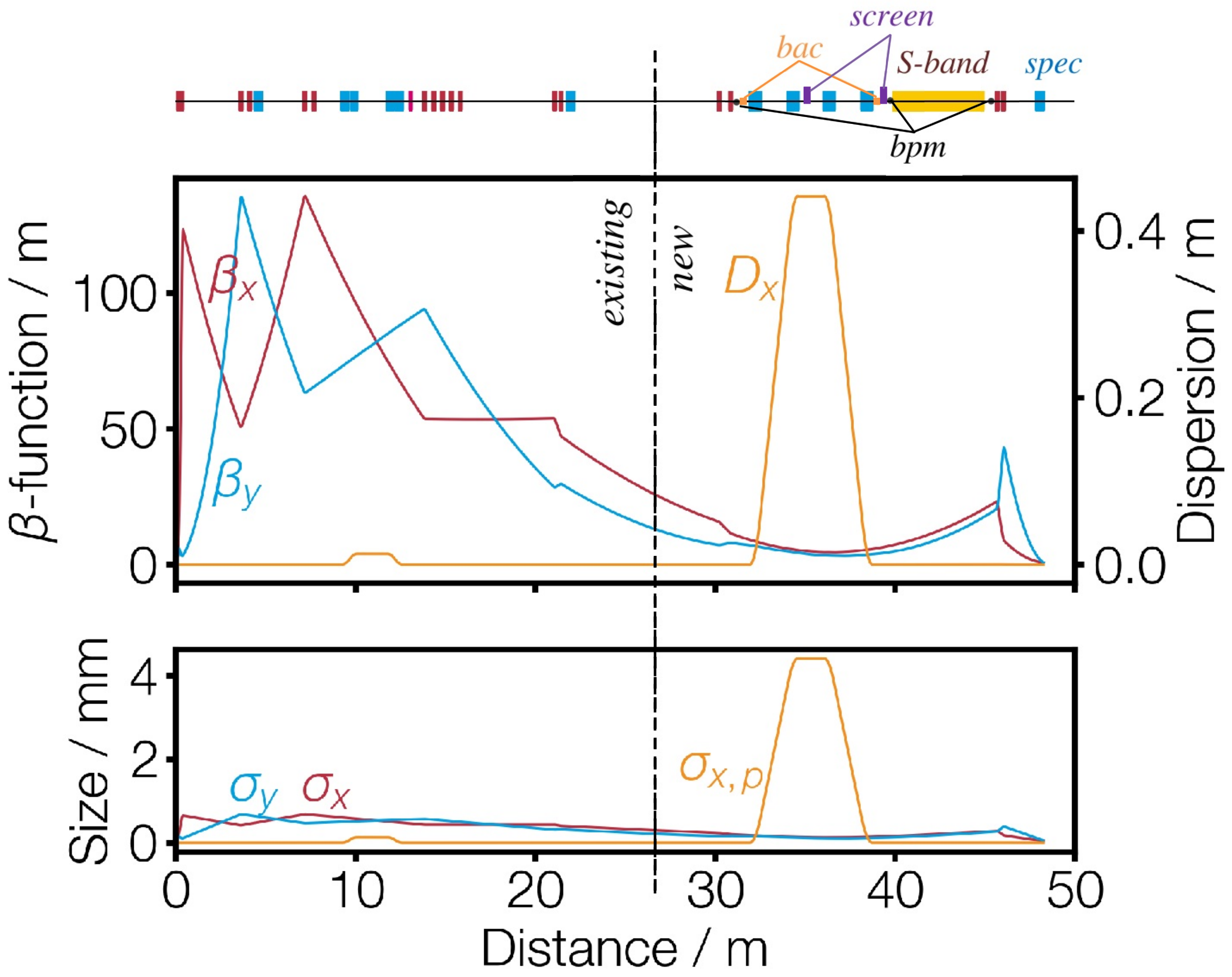


Separate LUX optics for the prototype test

Weaker focusing, large momentum acceptance

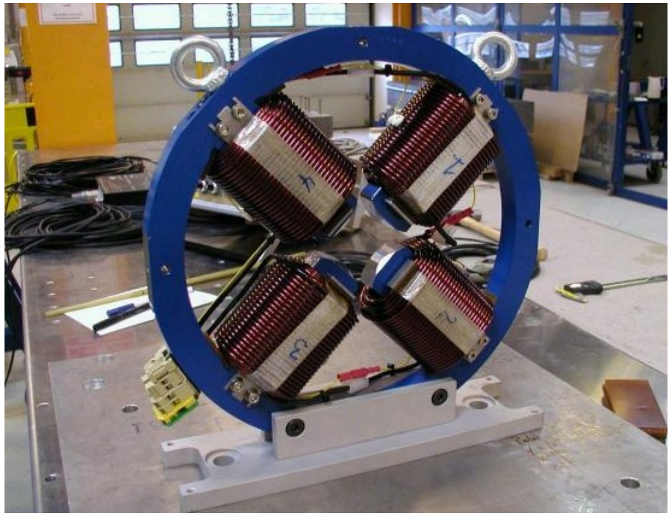
Additional diagnostics:

- 2 screen stations
- 3 BPMs
- 1 spectrometer
- 2 BAC (optional)



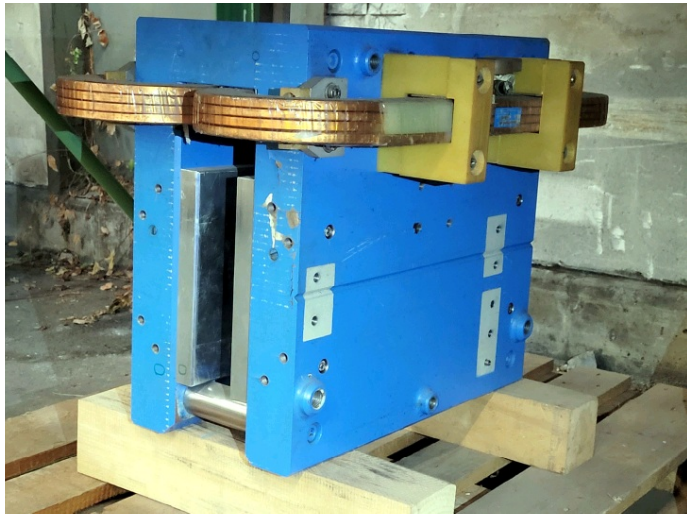
Magnets: use existing desings, refurbish

Getting the magnets by end next year seems feasibile



Quadrupoles - RQA

- Material for yoke available at DESY
- Coils need to be ordered
- Can be produced in 9-12 months (A. Petrov)



Dipoles - refurbished HERA/PETRA CV/CH

- Air gap to be reduced to 20 mm
- Max integrated field 0.14 Tm
- Good field width of 10 cm: allows tuning the R_{56}
- Require individual power supplies

S-band cavity: 3 GHz Linac II spare cavity module

Conventional, tested, and proven technology

Ready for rapid installation

- RF station available in the tunnel
- Using existing expertise of working with S-band
- Need a support structure
- About 2 mo conditioning time

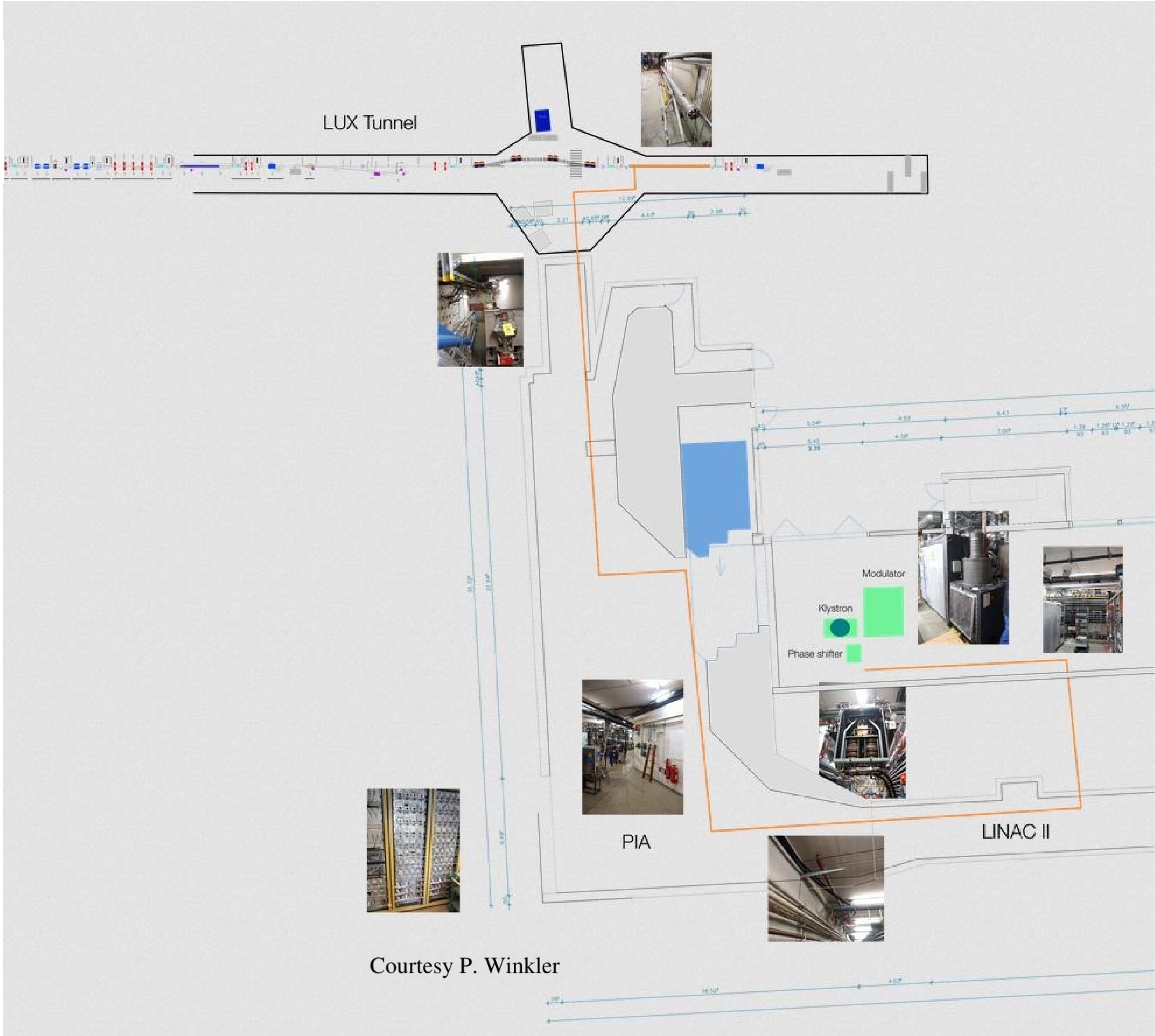
Operating frequency (40 C)	2 998 MHz
Active Length	5 m
Max gradient	20 MV/m
Max voltage	~ 100 MV
Operating voltage	20 - 30 MV

Step 1: Proof-of-principle prototype at LUX

Building up on the existing infrastructure

Minor changes to the existing beamline

- Add a chicane + S-band RF module
- Relocate the final spectrometer
- Adjust the photon diagnostic beamline



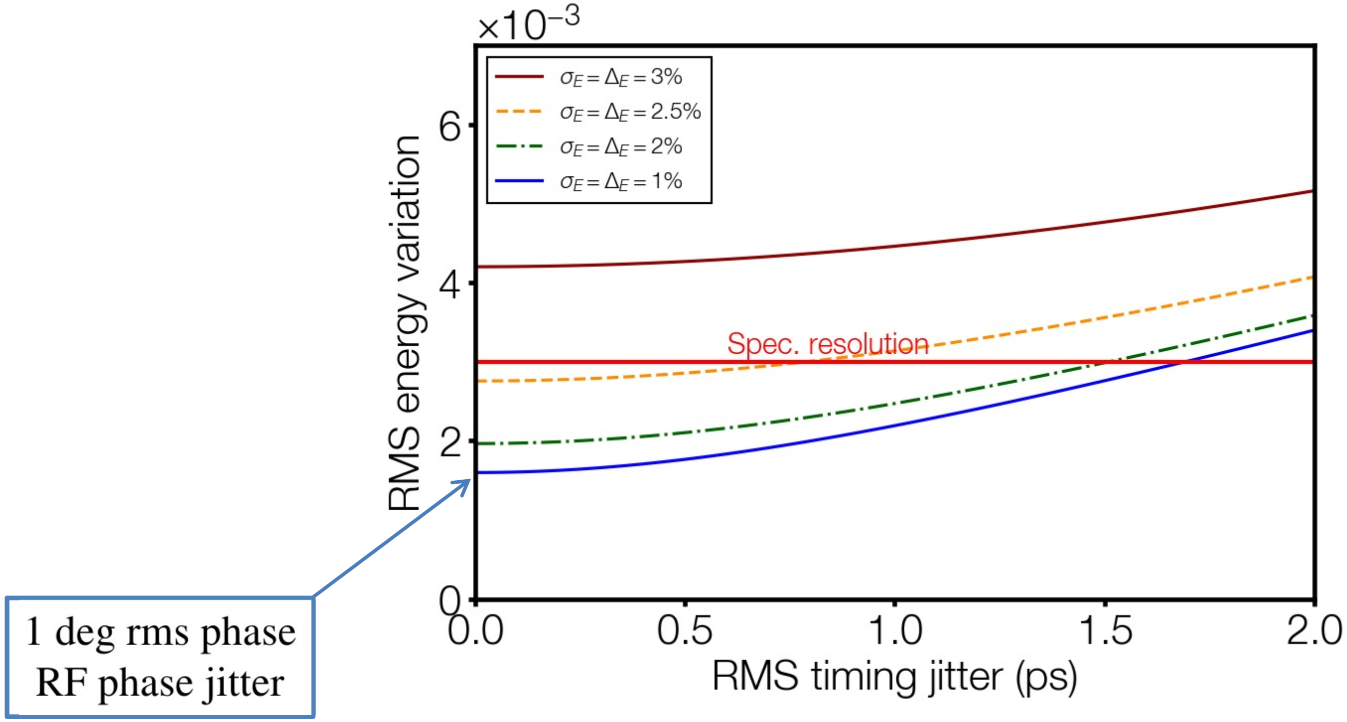
Courtesy P. Winkler

Laser-to-RF synch: Can tolerate 1 ps rms timing jitter

RF phase jitter might be an issue

Sources of final energy variation:

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



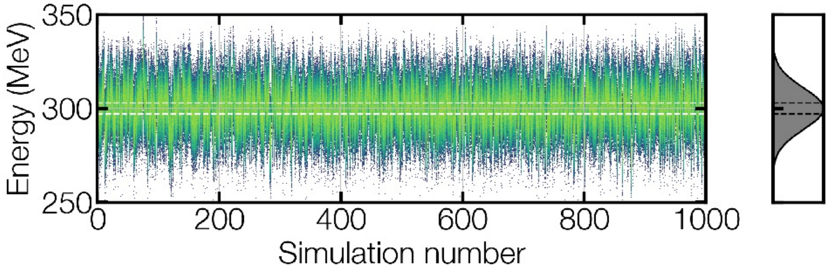
Expected performance

Reminder: We are building a bare minimum demonstrator, Fast & Cheap

Expected performance: Can achieve per-mille level of energy spread

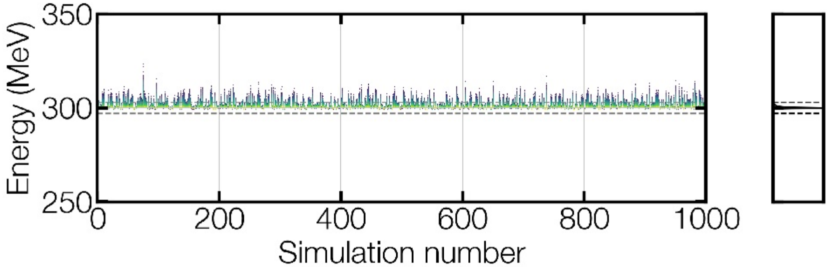
2% energy jitter + 3% energy spread + 200 fs rms timing jitter, no RF phase jitter

At LPA

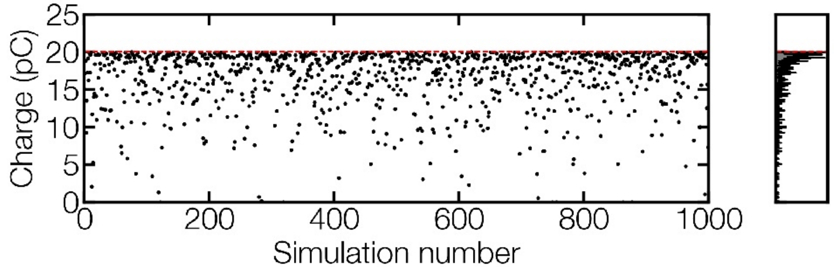


299.9 ± 11.1 MeV

After beamline



300.2 ± 0.3 MeV



18 ± 2 pC

With help of RF technology LPAs can achieve unprecedented levels of energy spread and stability

Crucial for practical applications such as injectors for future light sources

Offer competitive beam parameters for off-axis accumulation

- ~ 100 pC/shot, energy variation better than 10^{-3}
- High injection efficiency with realistic errors
- Compact, energy efficient

A proof-of-principle demonstrator is within reach

- Already existing infrastructure and technology
- Building up on the operational expertise of the LUX LPA
- Can be done in less than 2 years with minimum investment

Thank you

Step 1: Proof-of-principle prototype at LUX

Building up on the existing LUX infrastructure

Courtesy P. Winkler

Existing LUX beamline

- 500 MeV range LPA FEL demostrator
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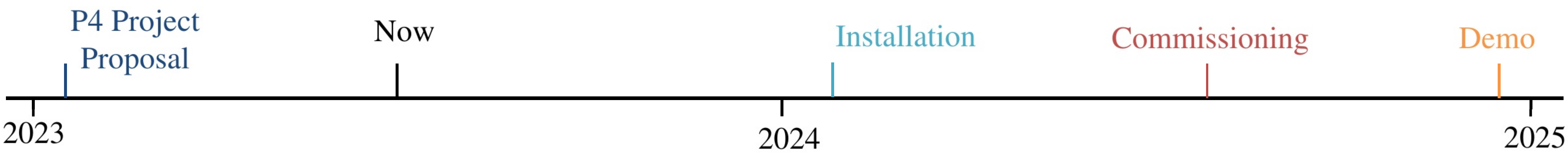
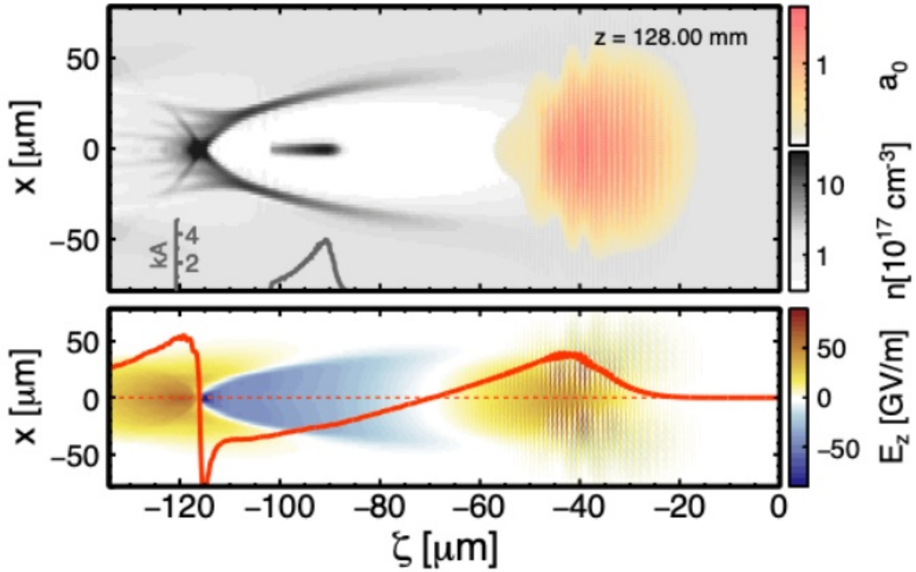


PIP4 @ DESY: 6 GeV with per-mille spread and jitter

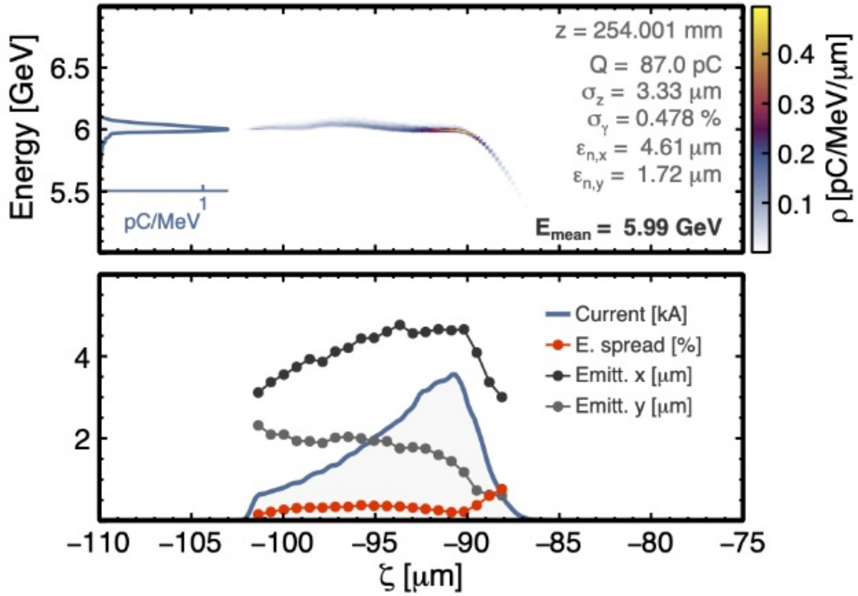
Simulated working point combining LUX approach with ideal guiding channels

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

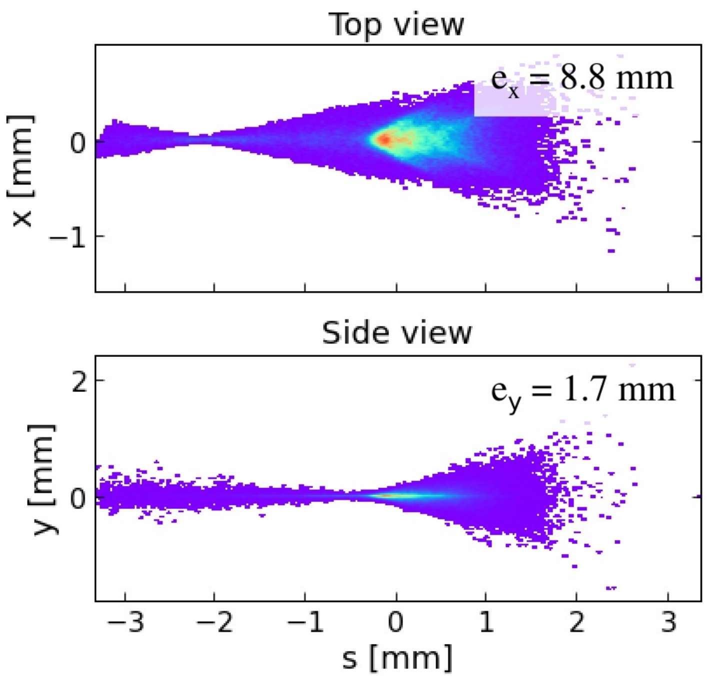


87 pC at 6 GeV with 0.5% energy spread

Chromatic correction

Preserving micron-level normalized emittance

Without chromatic correction



With chromatic correction