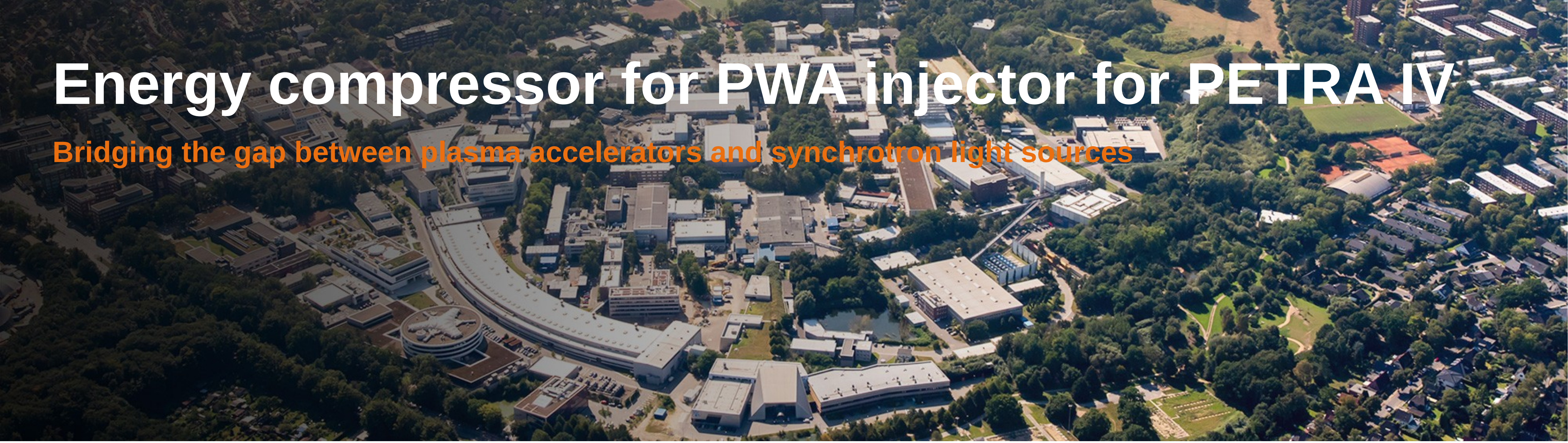
Energy compressor for PWA injector for PETRA IV

Bridging the gap between plasma accelerators and synchrotron light sources



Ilya Agapov, **Sergey Antipov**, Reinhard Brinkmann, Heiko Ehrlichmann, Ángel Ferran Pousa, Sören Jalas, Manuel Kirchen, Wim Leemans, Andreas Maier, Alberto Martinez de la Ossa, Jens Osterhoff, Eva Panofski, Rob Shalloo, Maxence Thévenet, Paul Winkler

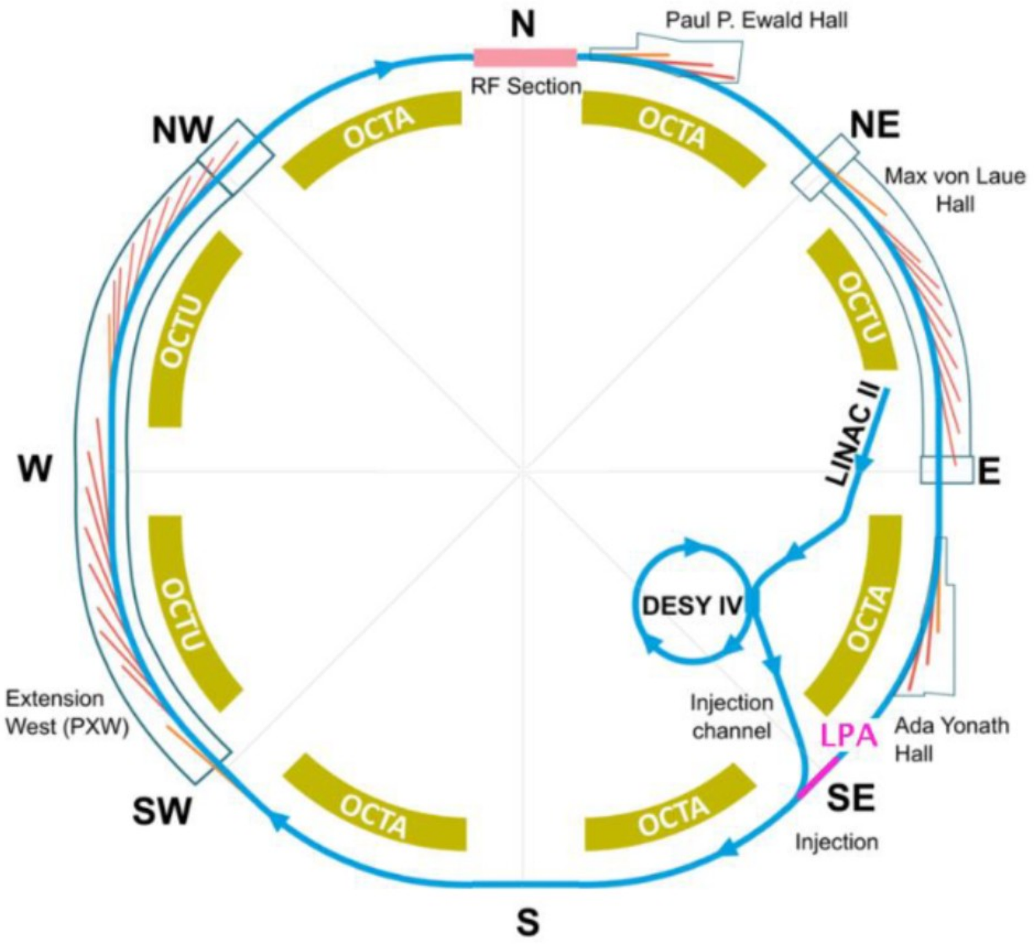
MT ARD ST3 Meeting, Berlin, Sep 9, 2022

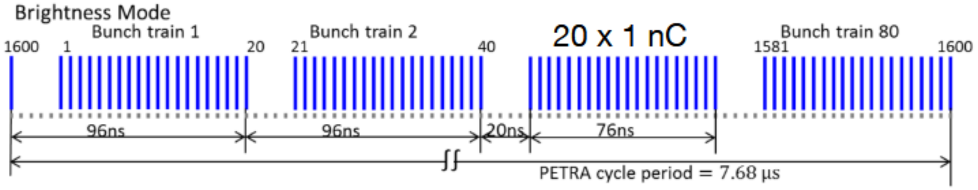
HELMHOLTZ

DESY.

The moonshot: LPA plasma injector for PETRA IV

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



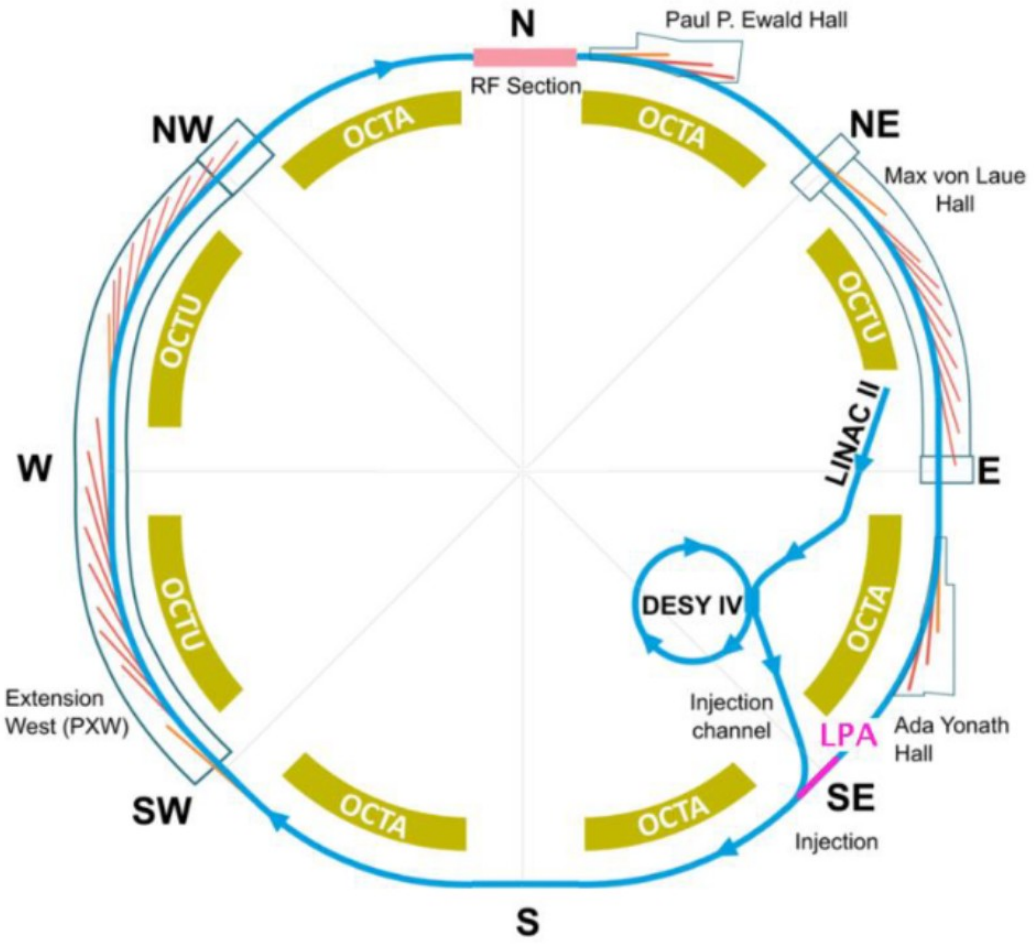


To compensate for beam losses and keep bunch-to-bunch charge variation within 10% need to top-up 100 pC at 0.5 Hz

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.

The moonshot: LPA plasma injector for PETRA IV

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



- 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.

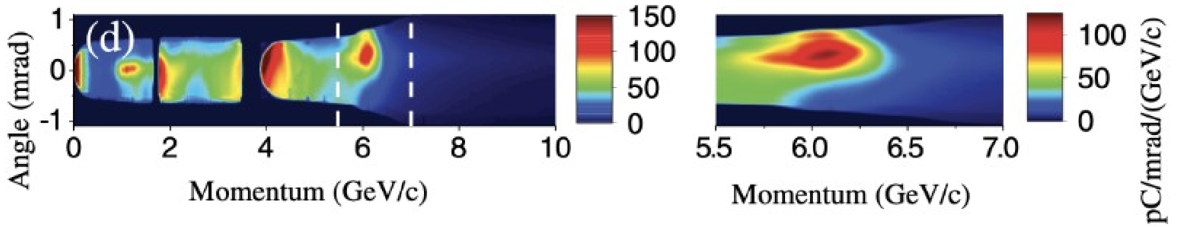
What is possible Today for Laser-Plasma Accelerators?

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)*

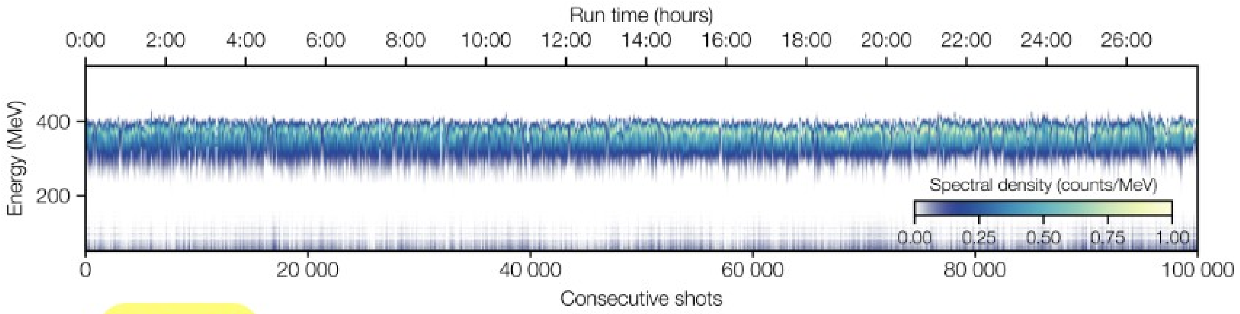


LUX@DESY: enhanced energy spread and stability

- 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)

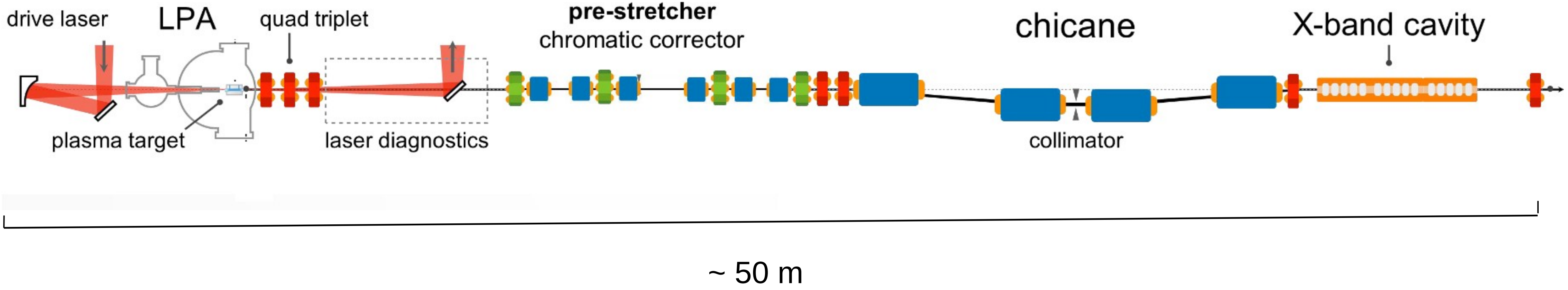
→ A. Maier et al., Phys. Rev. X 10, 031039 (2020)



1.8 % energy jitter

6 GeV beamline with X-band energy compression

Combining working, proven solutions



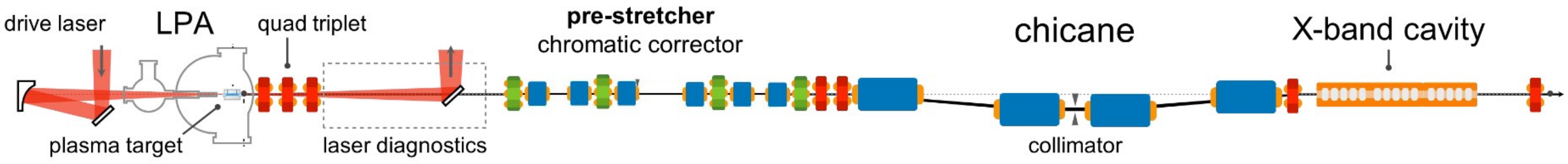
Capture triplet	50 cm, max G = 80 T/m
Pre-stretcher	R_{56} = 5 mm
Chrom. Sextupoles	30 cm, max S = 550 T/m^2
Main chicane	R_{56} = 10 cm, B = 1.45 T
Energy compressor	5 m, 12 GHz, 250 MV

→ 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

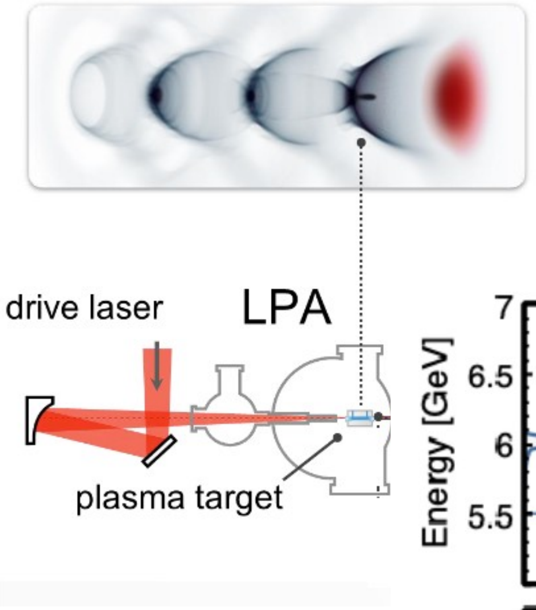
- Transport
- RF
- CSR
- Collimation

Elegant

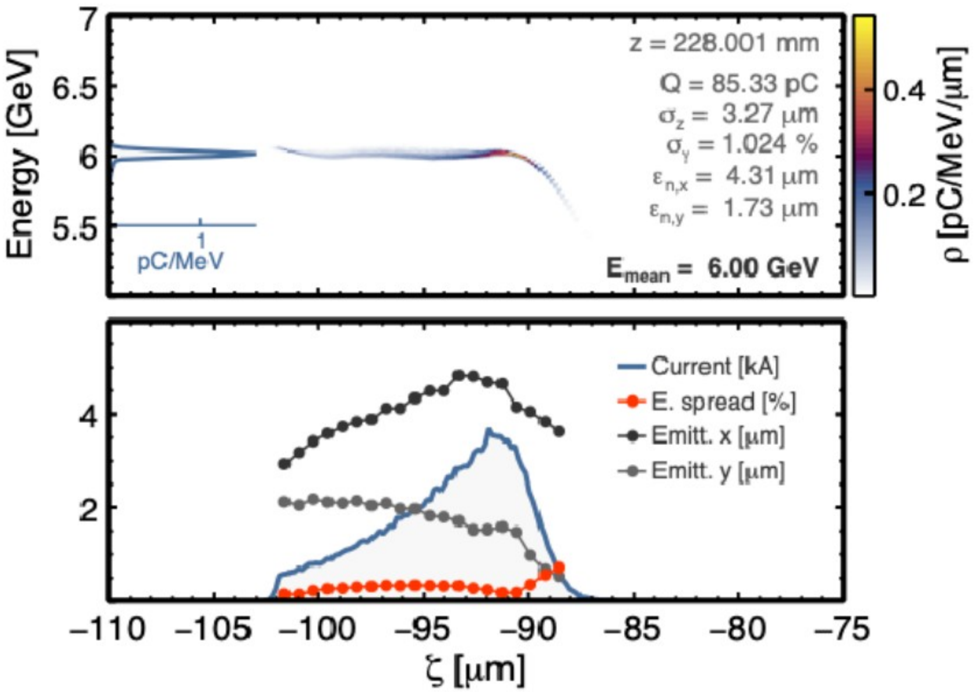
- Lattice errors
- 3rd harmonic RF
- Synch rad. damping
- Physical aperture

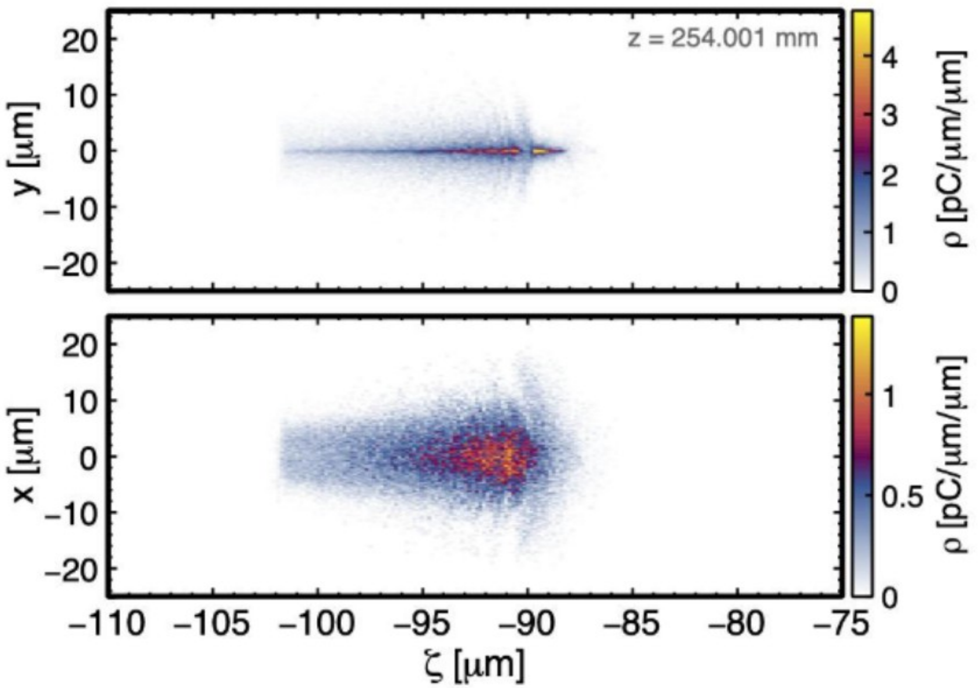
6 GeV LPA injector: the LPA

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



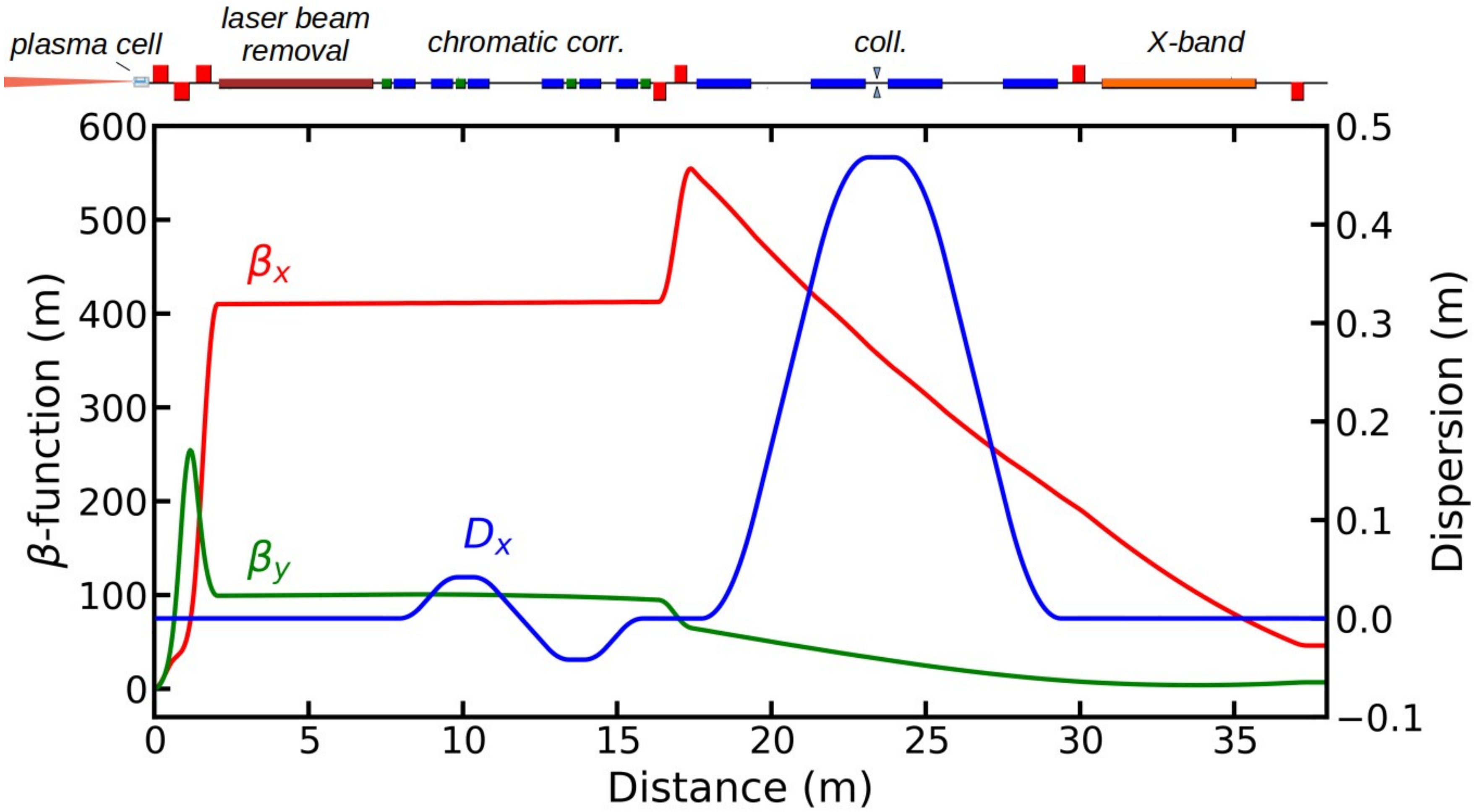
- A single 25-cm-long LPA stage
- Driven by a ~20 J laser pulse
- Bayesian optimization of the working point → S. Jalas et al., Phys. Rev. Lett. 126, 104801 (2021)





6 GeV LPA injector: the beamline

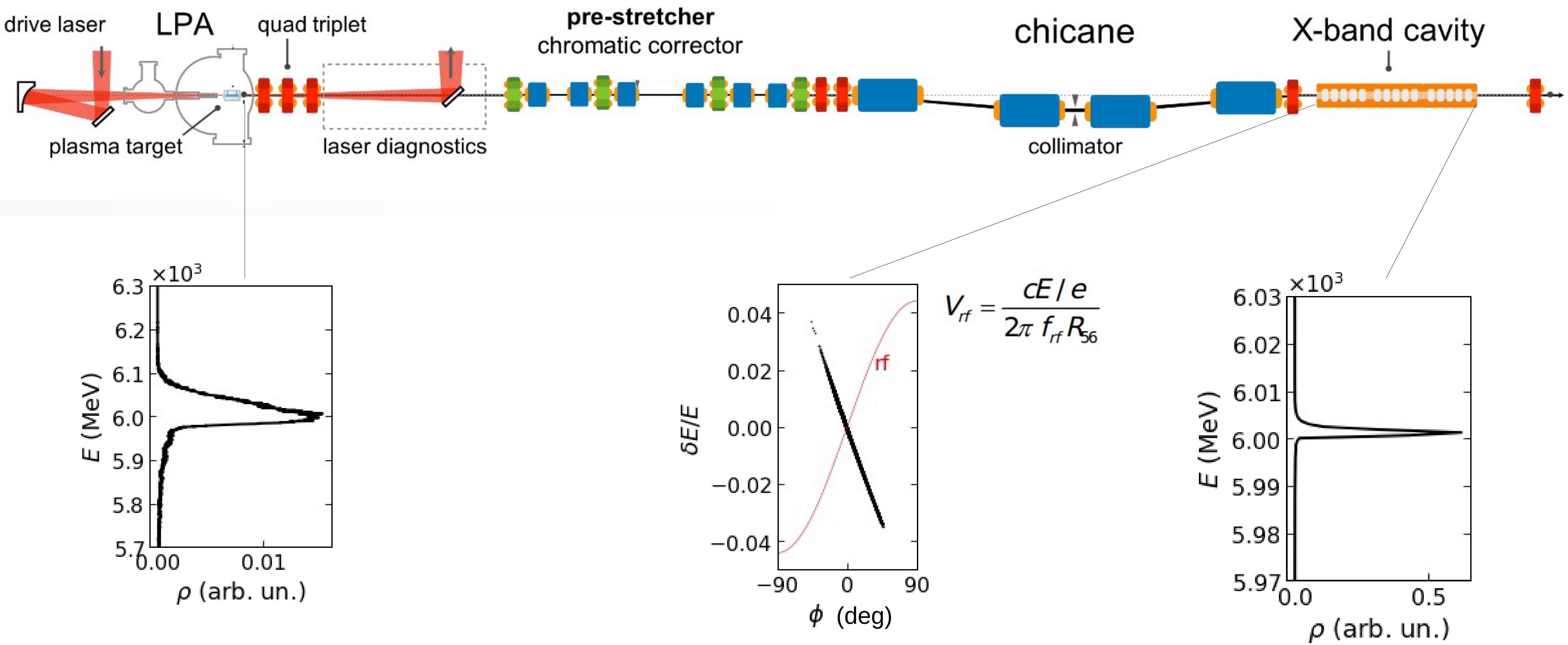
Beam capture, chromatic correction, energy compensation



→ S. A. Antipov et al., IPAC'22

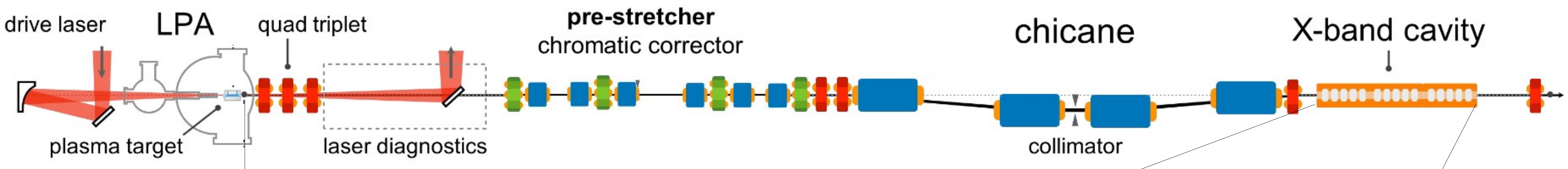
LPA energy spread correction

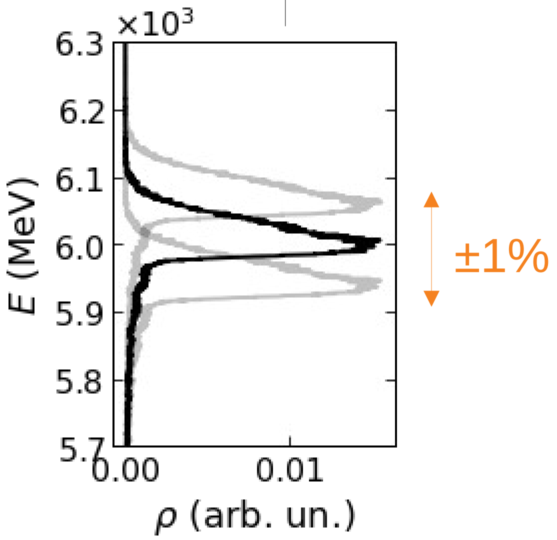
Improving the energy spread to sub-per-mille levels

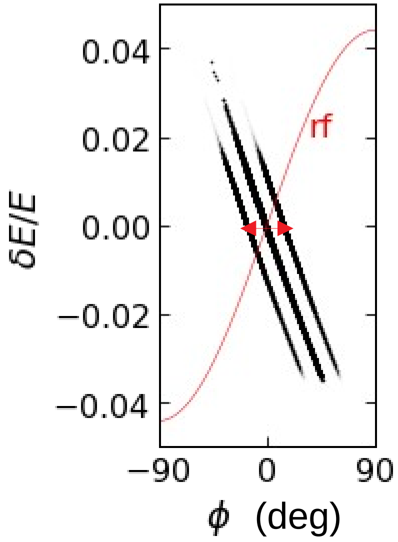


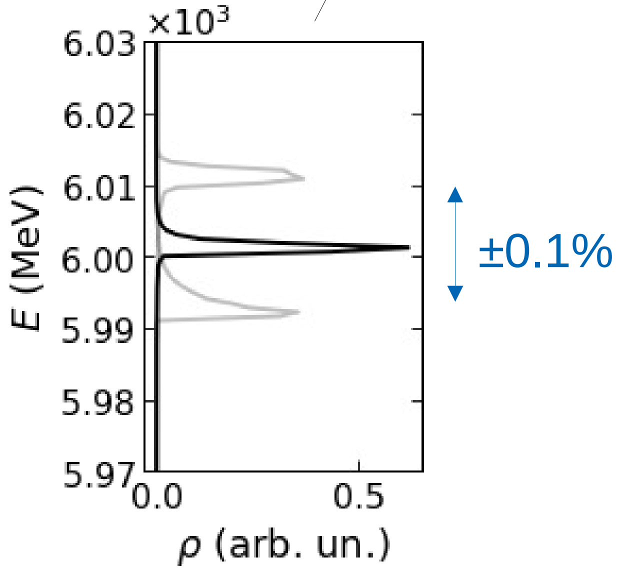
LPA energy spread correction

Achieving per-mille energy stability



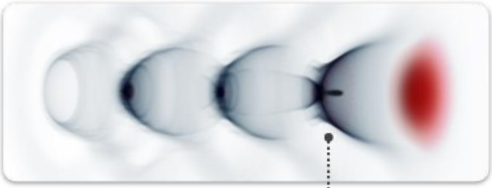






6 GeV LPA performance

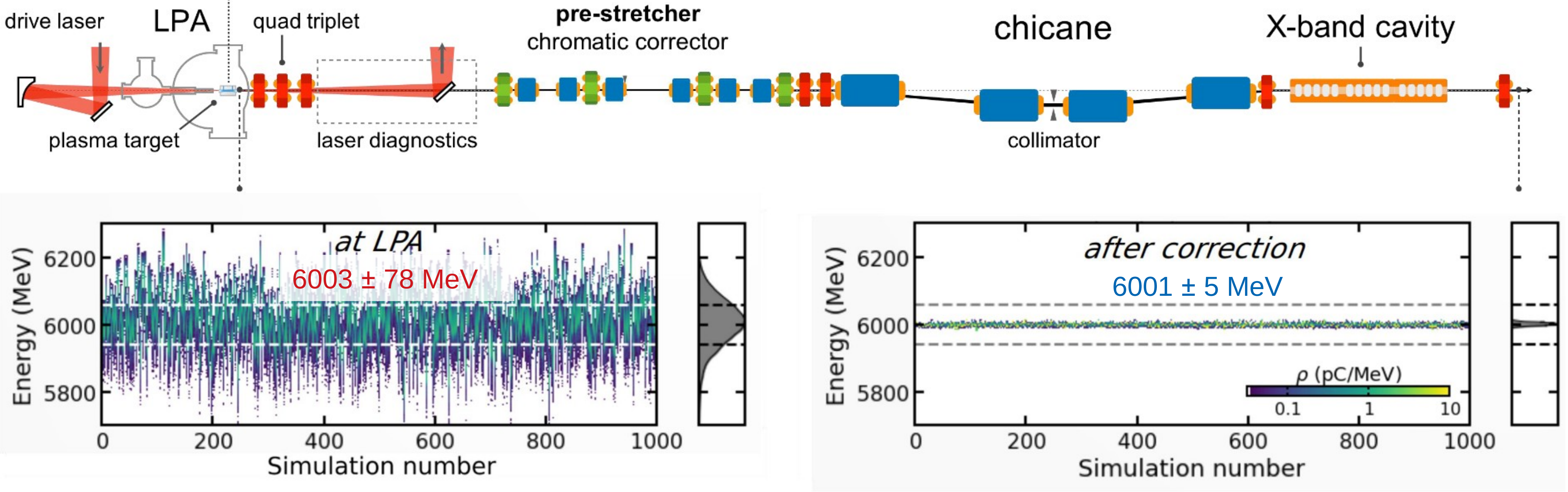
Sub-per-mille energy spread and stability for future storage rings



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

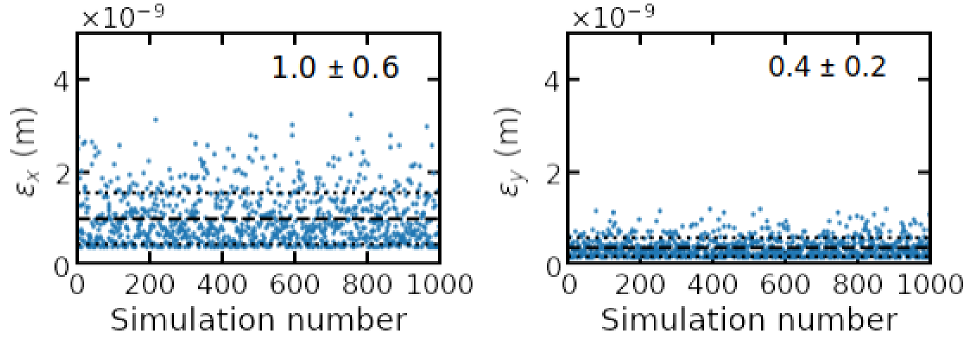
Final emittance – about **1 nm-rad**

- Assuming a realistic laser pointing angle fluctuation (rms fluctuation = rms divergence)
- For comparison, DESY-IV will provide 19, 2 nm-rad

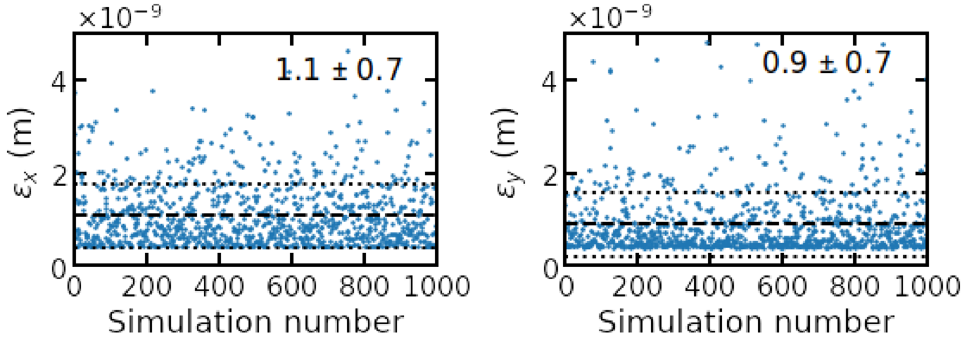
Start-to-end injection efficiency simulation:

- Element-by-element simulation in ELEGANT
- Realistic 5% β-beating
- Simulated 20 machines, small losses in 1 case
- No beam rotation or aperture sharing required

- Before capture

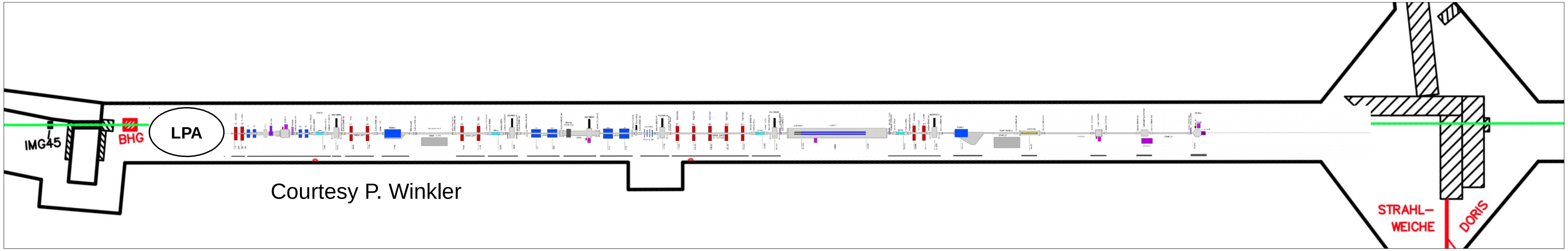


- At the exit of the beamline



Step 1: Proof-of-principle prototype at LUX

Goal: demonstrate record energy spread, stability of LPA beam



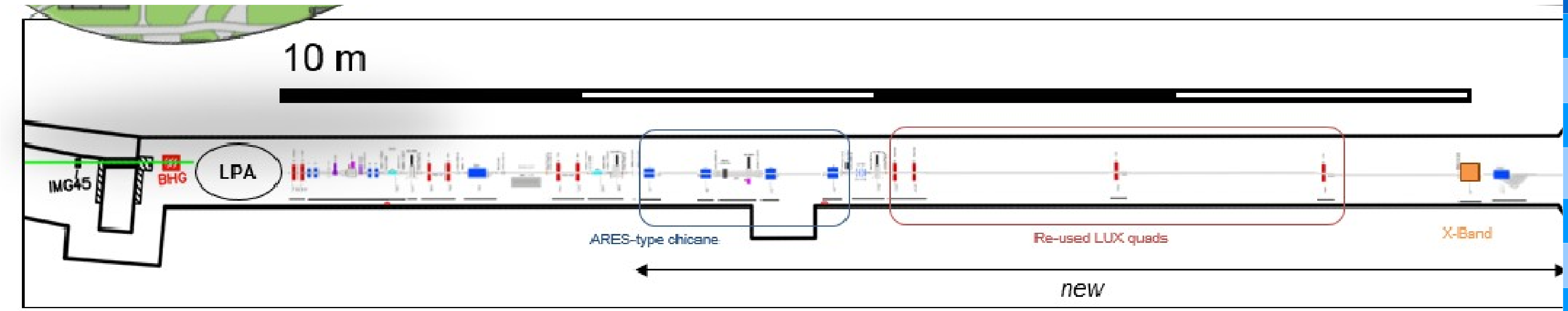
Courtesy P. Winkler

Existing LUX beamline

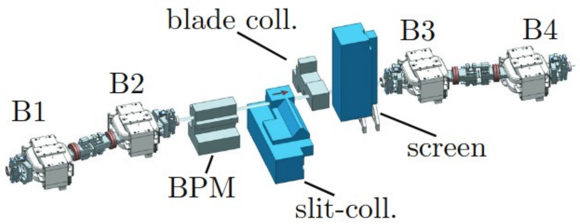
- 500 MeV range LPA FEL demostrator
- Record (for an LPA) 24-h-long continuous run
- Beam screens and spectrometers for diagnostics

Proof-of-principle prototype at LUX

‘Building blocks’

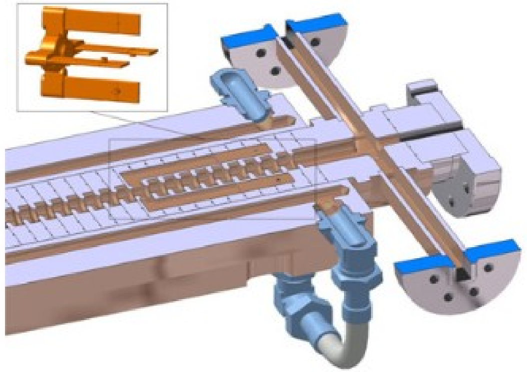


Beam energy	300 MeV
Charge	~ 20 pC
Rep. Rate.	~ 1 Hz
Capture quads	< 100 T/m
Chicane	R_{56} = 5 cm
RF	12 GHz, 20 MV
Laser-rf-synch	~ 100 fs rms
Final energy var.	~ 10^{-3}
Final norm. emit.	~ 1 μm



→ Lemery *et al*, *IPAC’17*

CERN/PSI 12 GHz X-band cavity



→ L.S. Cowie *et al.*, *IPAC’18*

+ 6 MW X-Band RF (PolariX TDS)

+ Laser-to-rf synch. (FLASH, ARES)

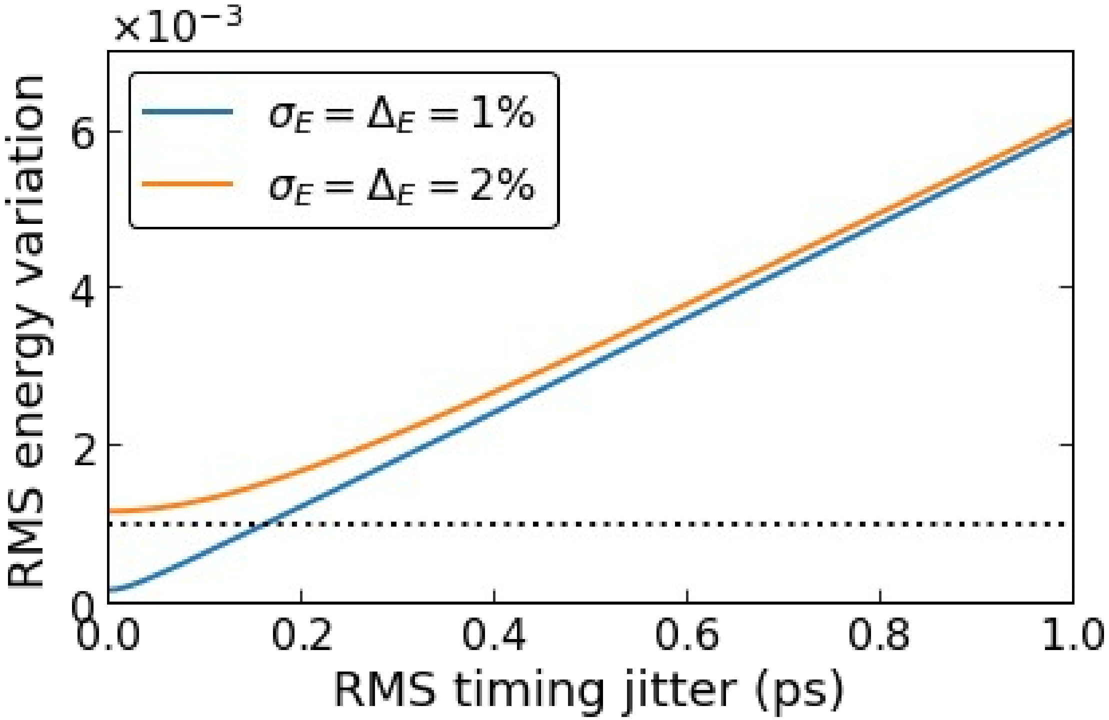
+ 3 GHz bunch arrival cavity for diag.

Laser-to-RF synch: Can tolerate 100-200 fs rms timing jitter

Achievable with an all-RF synchronization system

Sources of final energy variation:

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



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

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 about 2 years

Thank you

Check out our latest paper

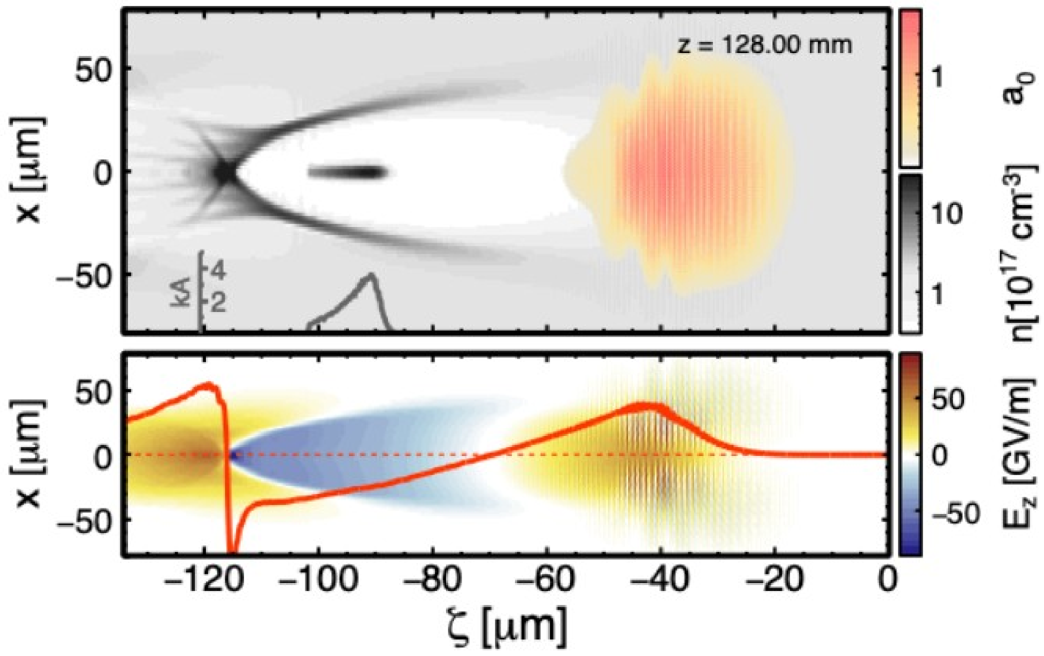
Á. Ferran Pousa et al., Phys. Rev. Lett. 129, 094801

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

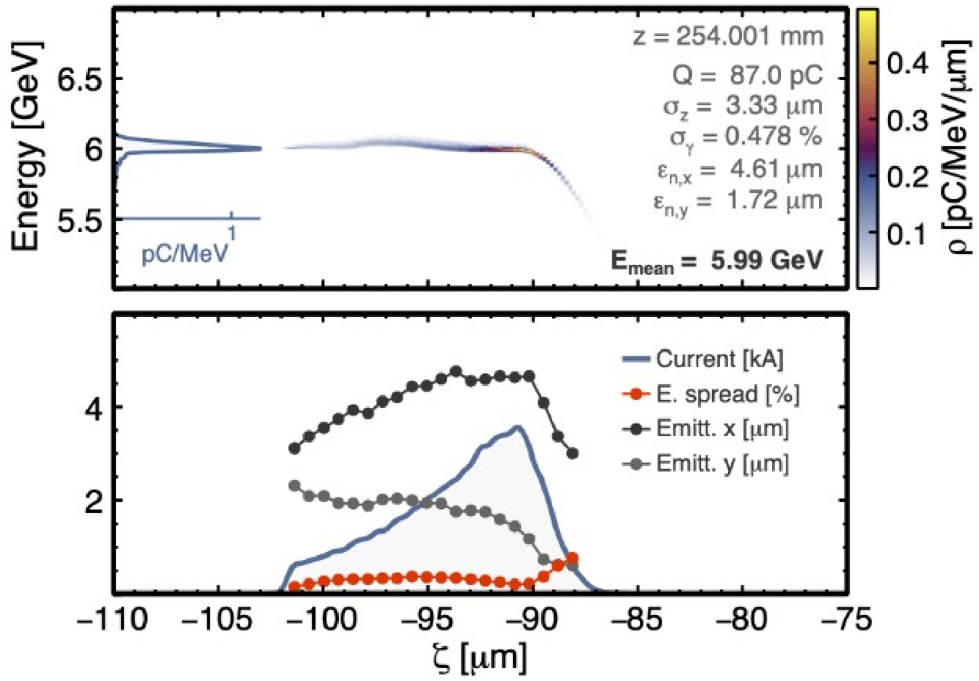
Simulated working point combining LUX approach with ideal guiding channels

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

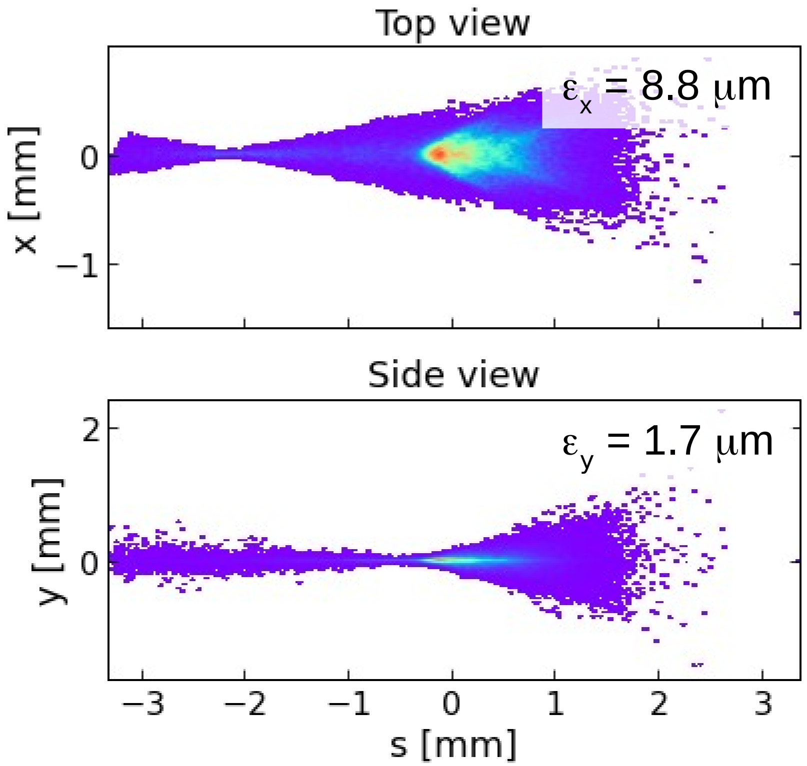


87 pC at 6 GeV with 0.5% energy spread

Chromatic correction

Preserving micron-level normalized emittance

Without chromatic correction



With chromatic correction