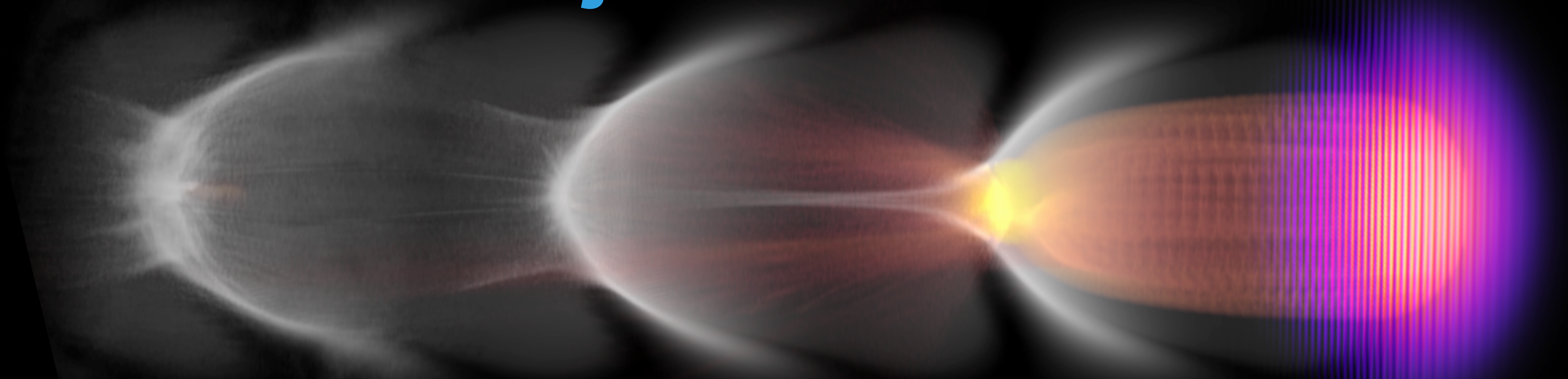
The Plasma Injector for PETRA IV.



Conceptual Design Report

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

DESY. Deutsches Elektronen-Synchrotron: MPY / MPA / MLS

*speaker: alberto.martinez.de.la.ossa@desy.de

HELMHOLTZ

Future Light Sources Workshop (FLS 2023), Lucerne.

PETRA IV. The Ultimate 3D X-ray Microscope

The future 4th generation synchrotron light source at DESY

Pushing the limits in photon science

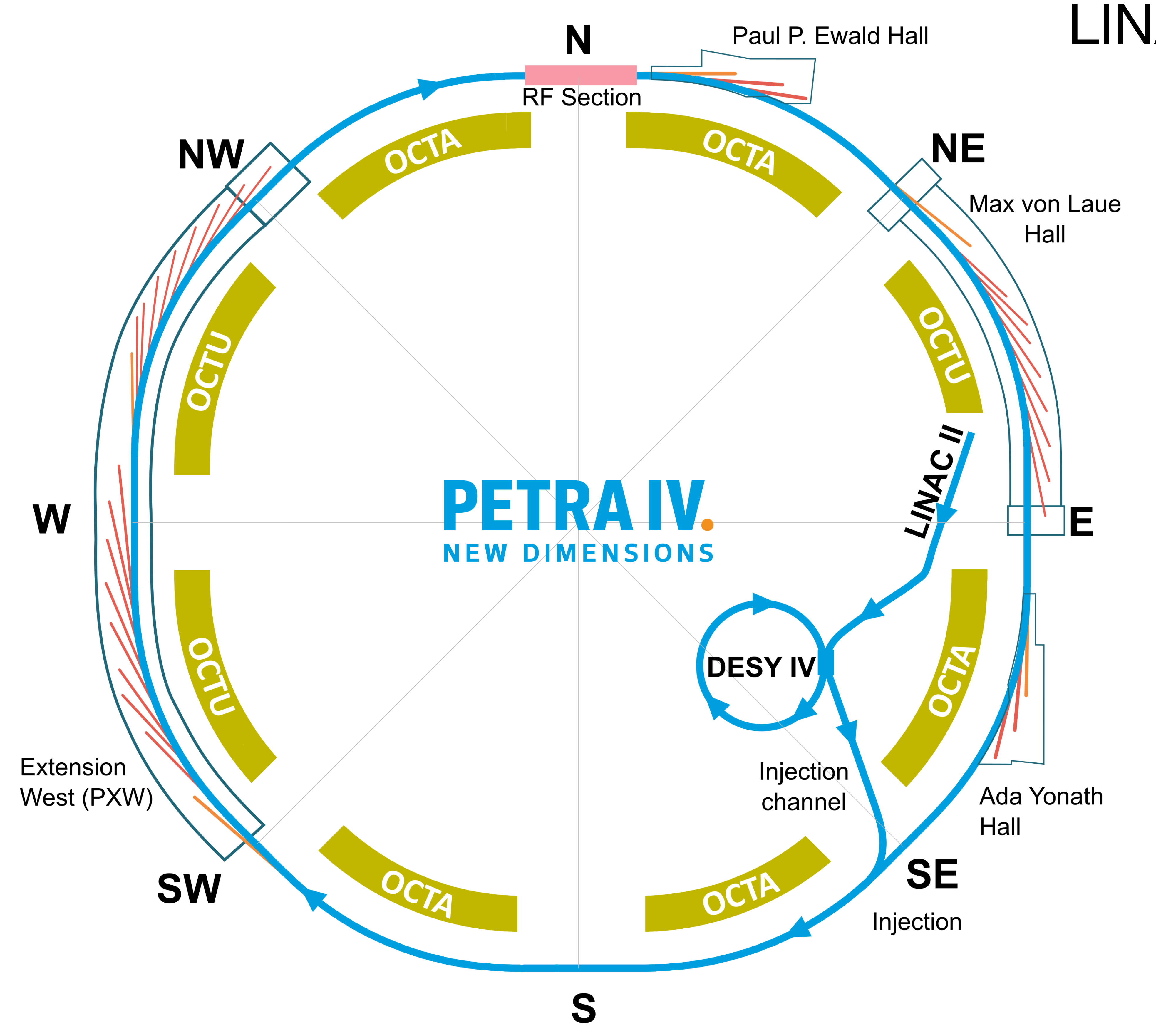
- PETRA IV will provide 100 — 1000 times higher brightness beams than PETRA III.
- New Extension West Hall doubles the number of photon beamlines (30): ~10,000 user/yr.
- PETRA IV will become a world reference in 3D X-ray microscopy, driving ground-breaking discoveries in health, energy, mobility, information technology, earth and environment.
- PETRA IV supports new technologies and sustainability concepts for the future, e.g. plasma acceleration technology.

PETRA IV – Decoding Complexity in Nature and Technology

PETRA IV - Conceptual Design Report

PETRA IV: The (conventional) Injector system

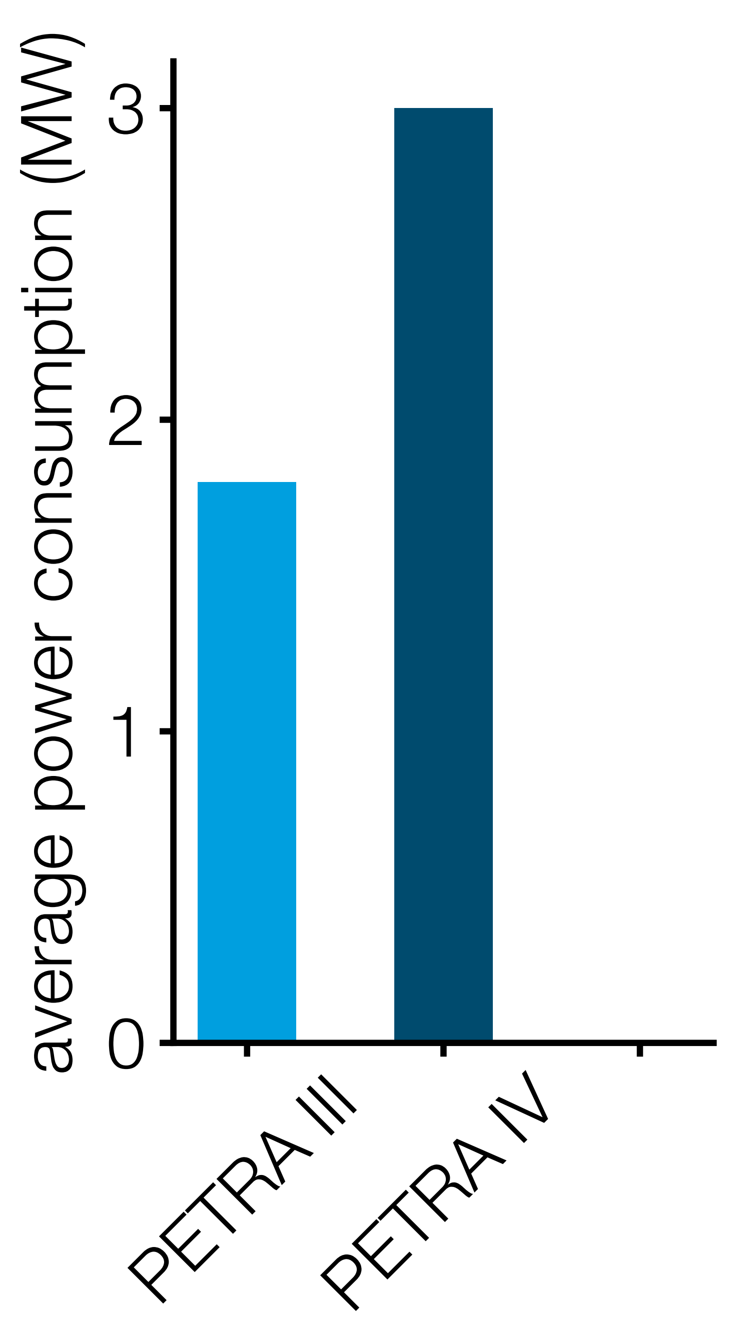
A new synchrotron booster is needed: DESY IV

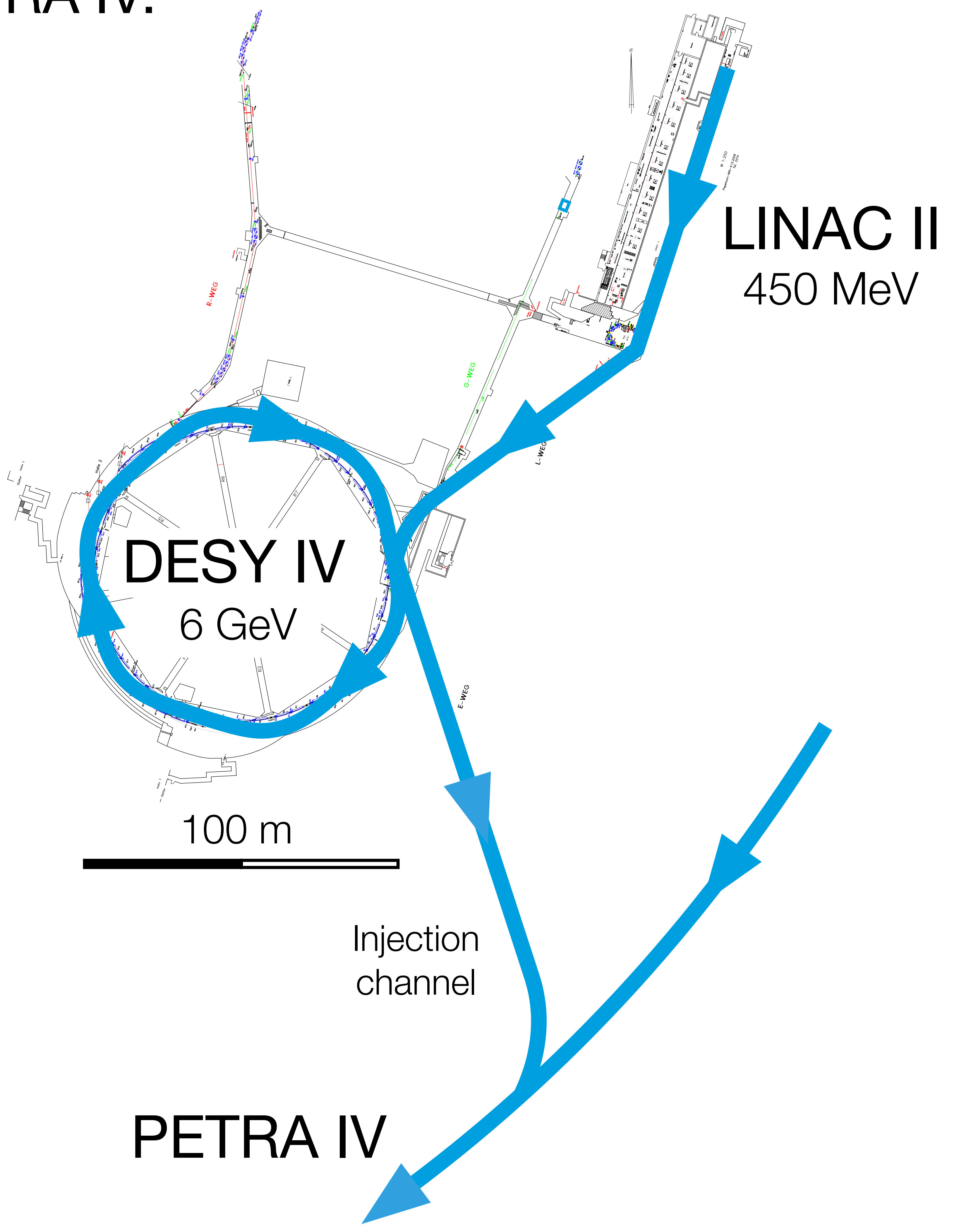


circumference: 2.3 km

Conventional injector for PETRA IV:
LINAC II + DESY IV

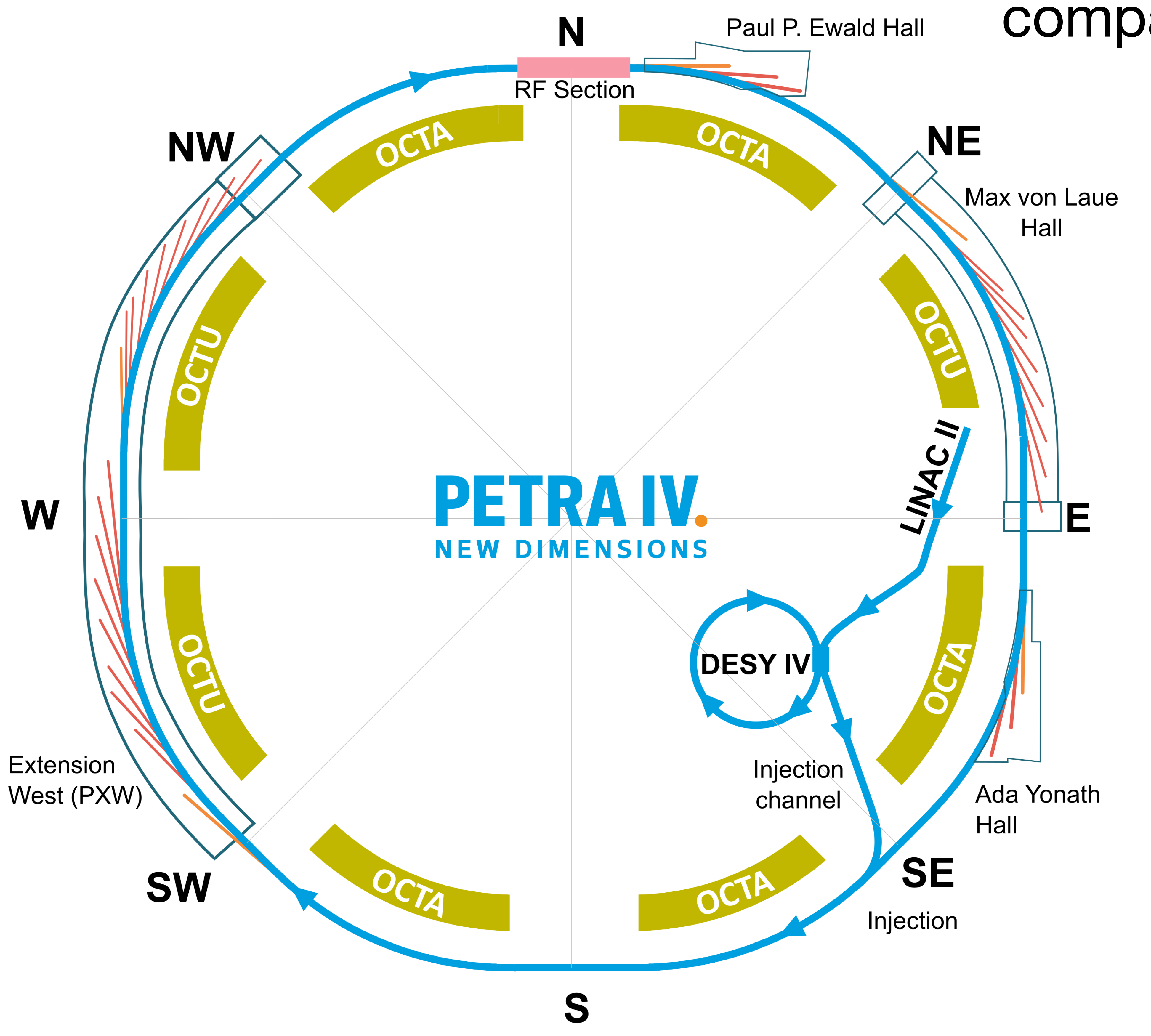
Injector power usage





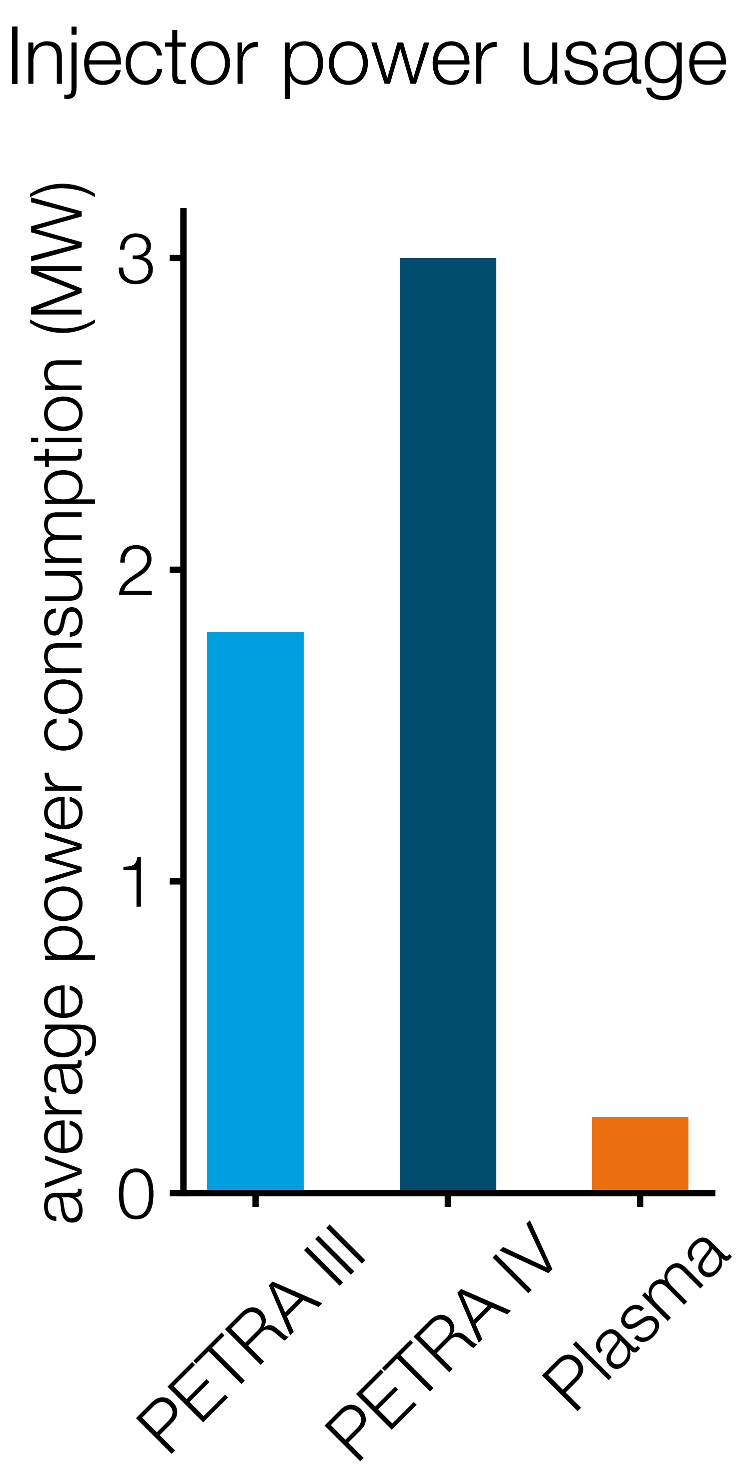
The Plasma Injector for PETRA IV

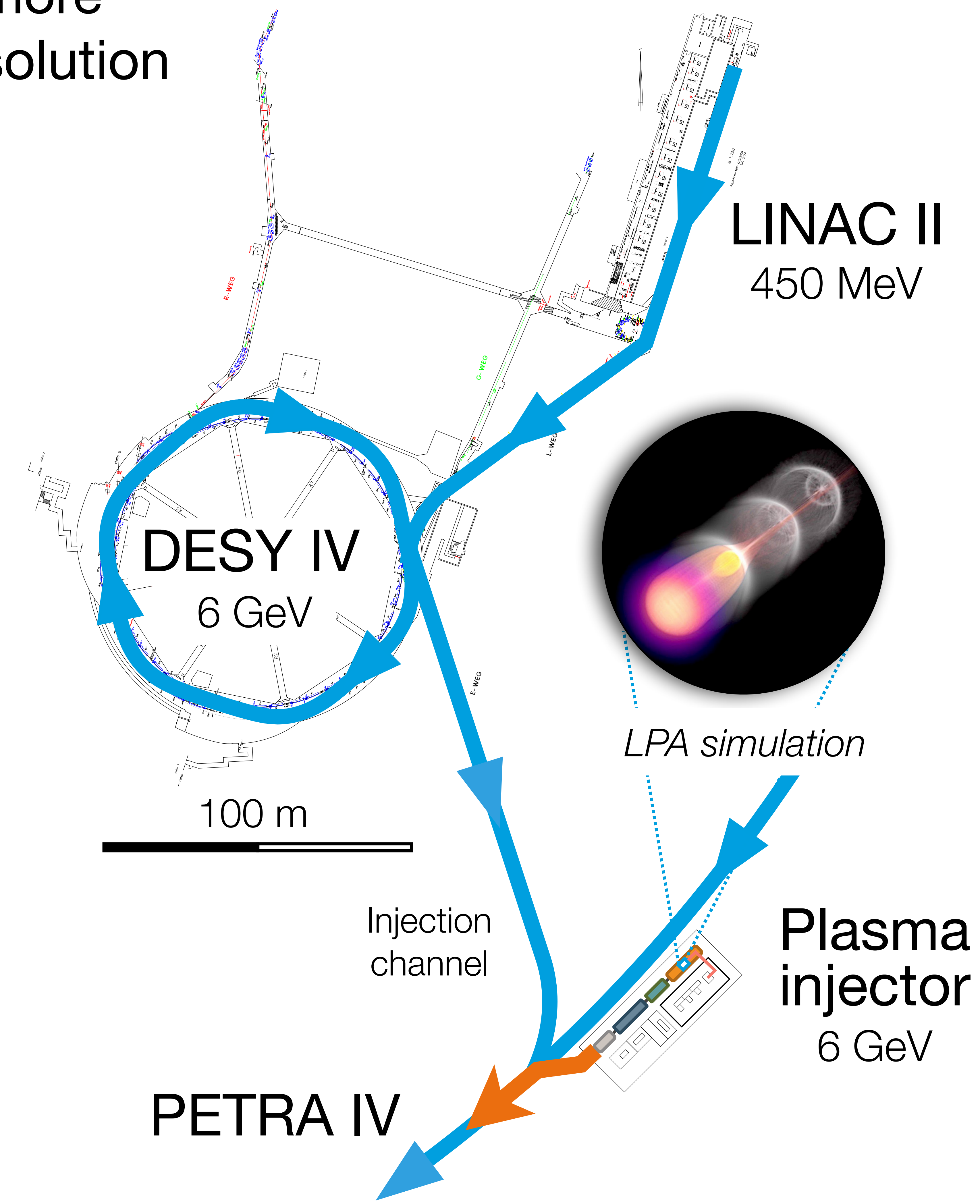
a competitive, compact and cost-effective alternative to conventional technology



circumference: 2.3 km

LPA technology can enable a more compact and energy efficient solution





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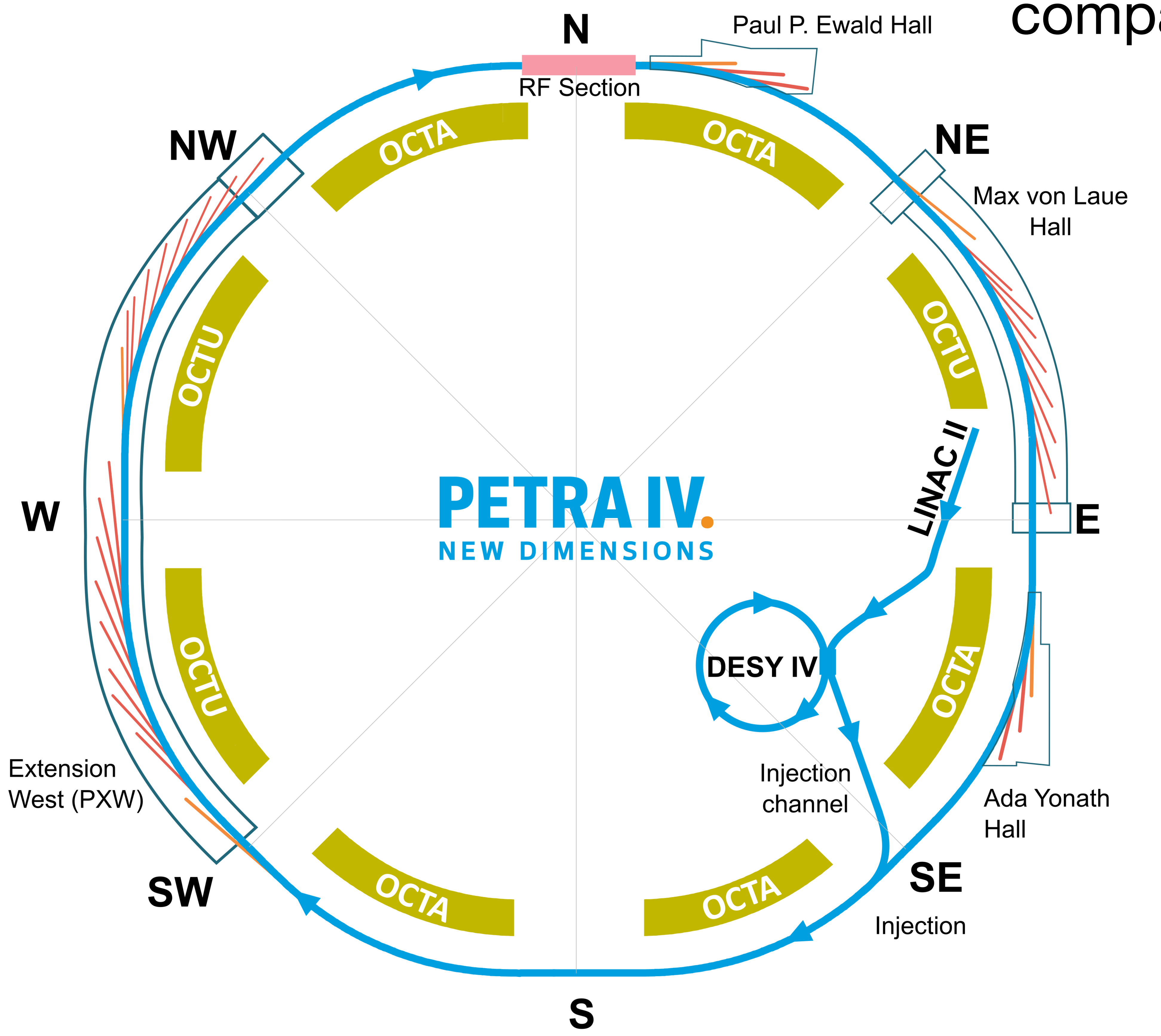
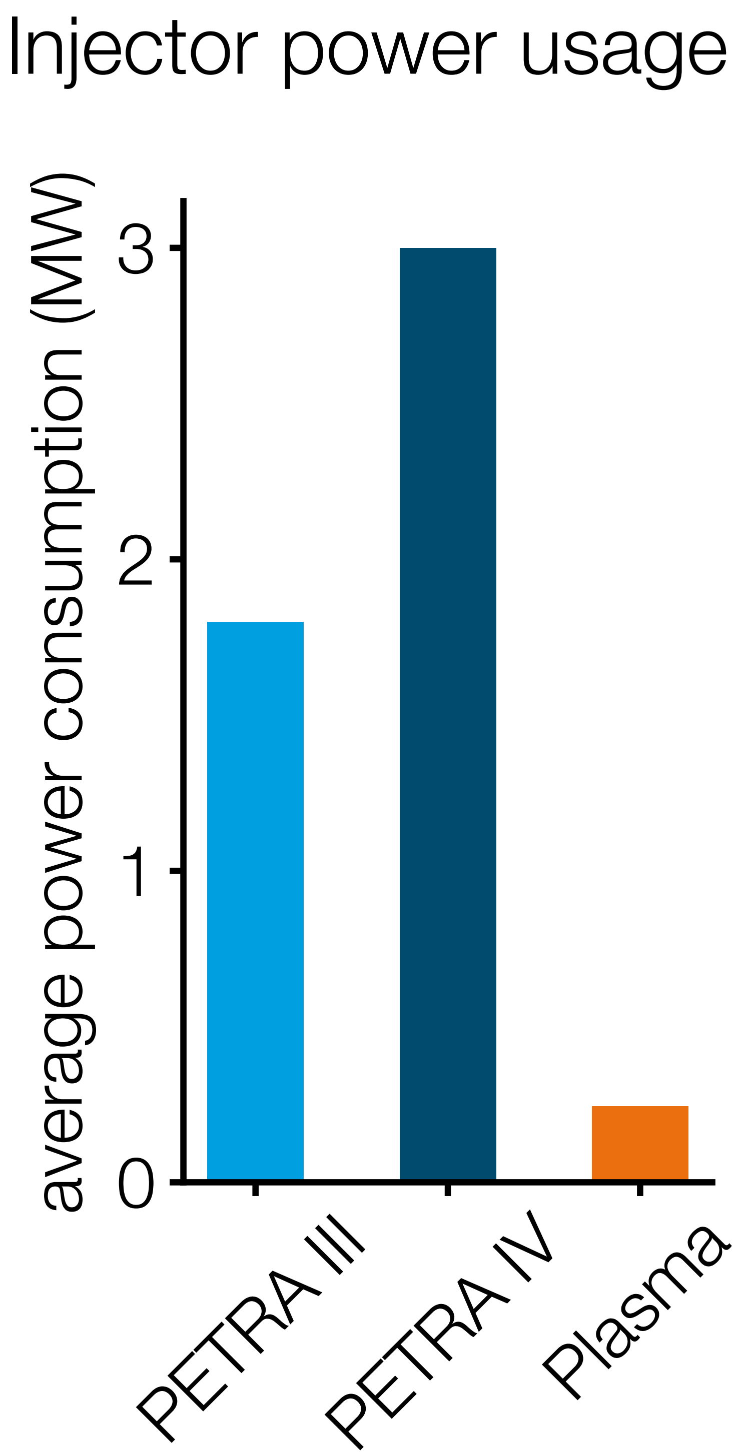
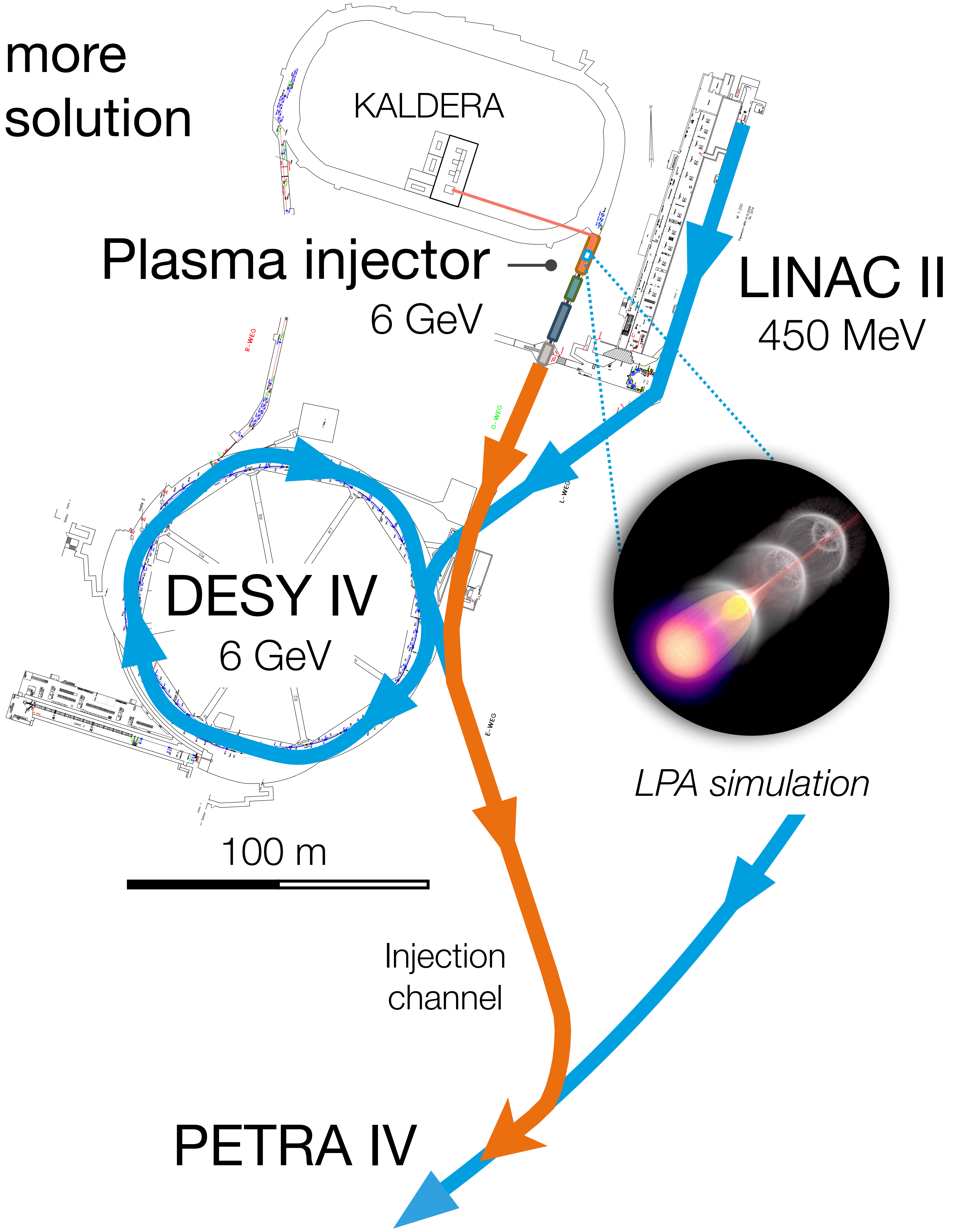


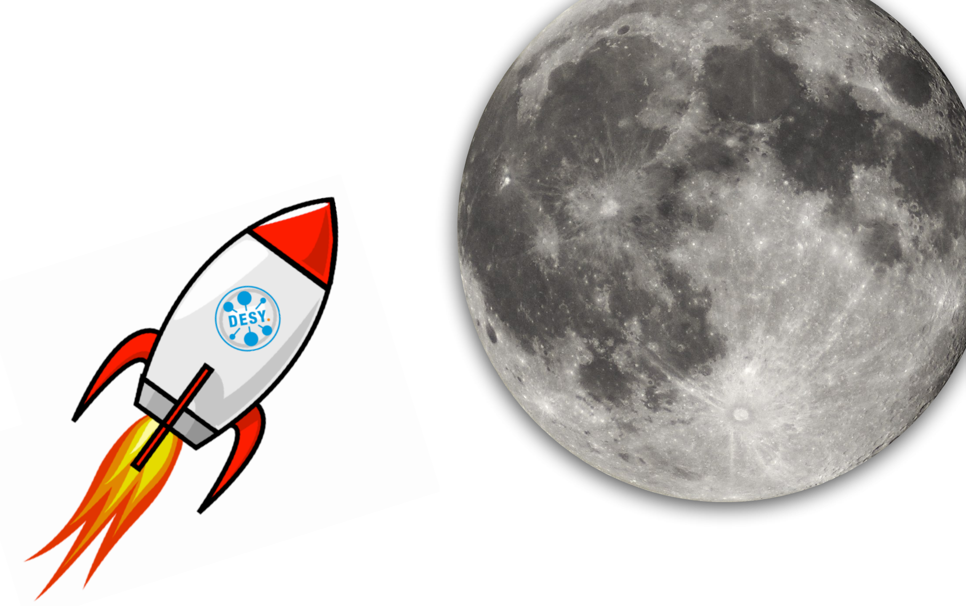
circumference: 2.3 km





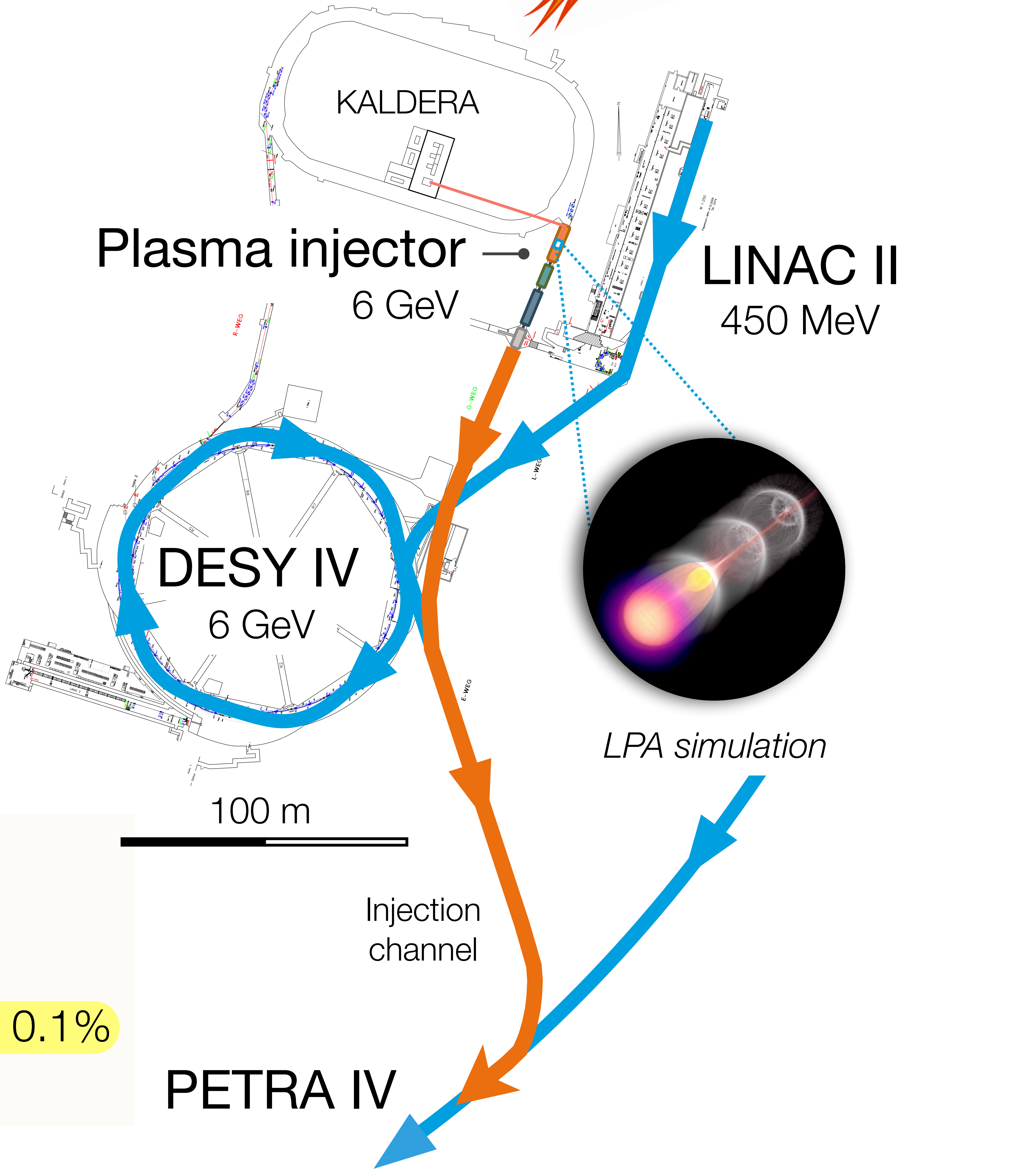
The Plasma Injector for PETRA IV

a competitive, compact and cost-effective alternative to conventional technology

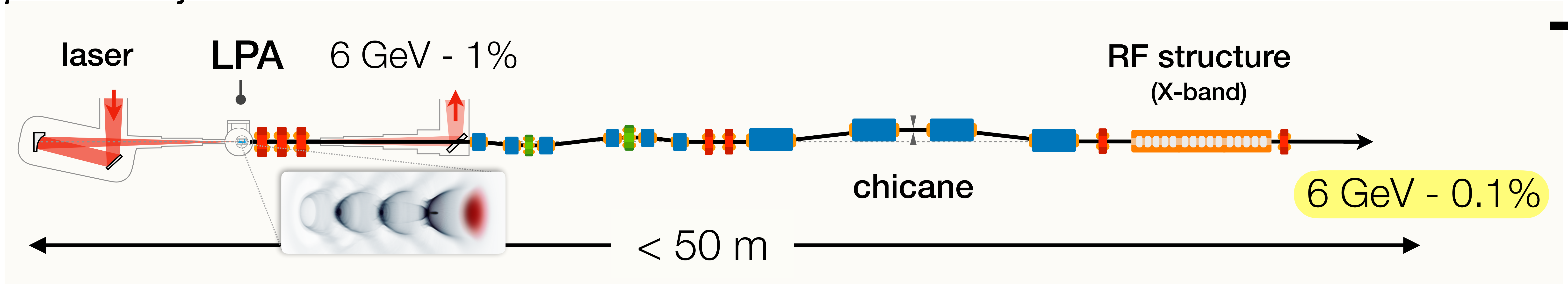


Enabling laser plasma accelerators (LPAs) for top applications

- 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).
- Laser guiding technologies for efficient 6 GeV energy gain (HOFI).
- 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 schematic



PETRA IV: injection requirements

Momentum acceptance → 0.1% energy spread and jitter

PETRA IV acceptance:
accumulation mode (off-axis injection)

- Momentum acceptance: 1%
- Transverse acceptance: 50 nm rad

Beam parameters:

- **Energy: 6 GeV**
- **Energy spread and jitter <~ 0.1%**
- Normalized emittance <~12 µm

Injection rate:

- User availability >98% ➟ Filling time < 10 min
- Total charge >99% ➟ Top-up period < $T_{1\%}$

PETRA IV design parameters

Operation mode	Brightness	Timing
Total charge / nC	1536	640
Bunch charge / nC	0.8	8.0
Number of bunches	1920	80
Bunch spacing / ns	4	96
Beam lifetime / h	10	5
Top-up period / m	6	3

$Q(t)/Q_0 = \exp(-t/\tau)$ — beam lifetime

beam charge drops by 1% in $T_{1\%} = -\ln 0.99\,\tau$

Injection rate		
Initial filling	**> 2.6 nC/s**	> 1.1 nC/s
Top-up	> 43 pC/s	> 36 pC/s

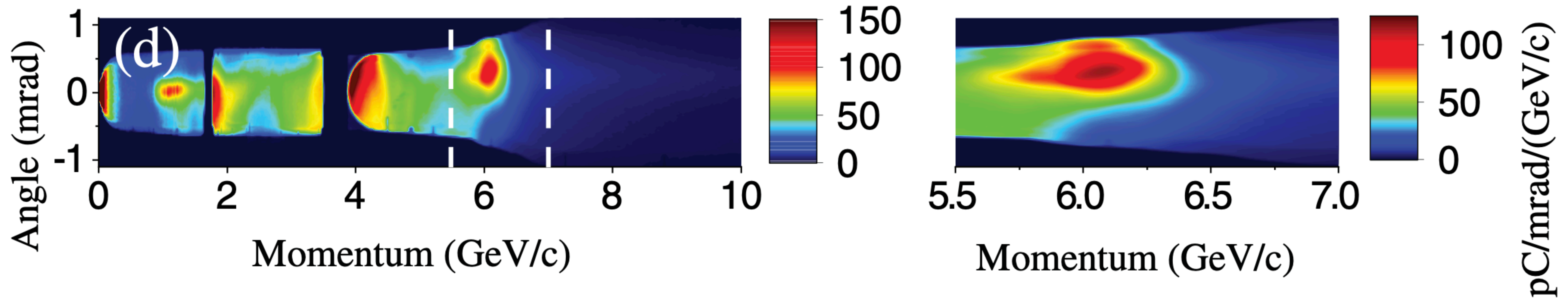
What is possible today for Laser-Plasma Accelerators?

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

BELLA@LBNL: multi-GeV acceleration

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

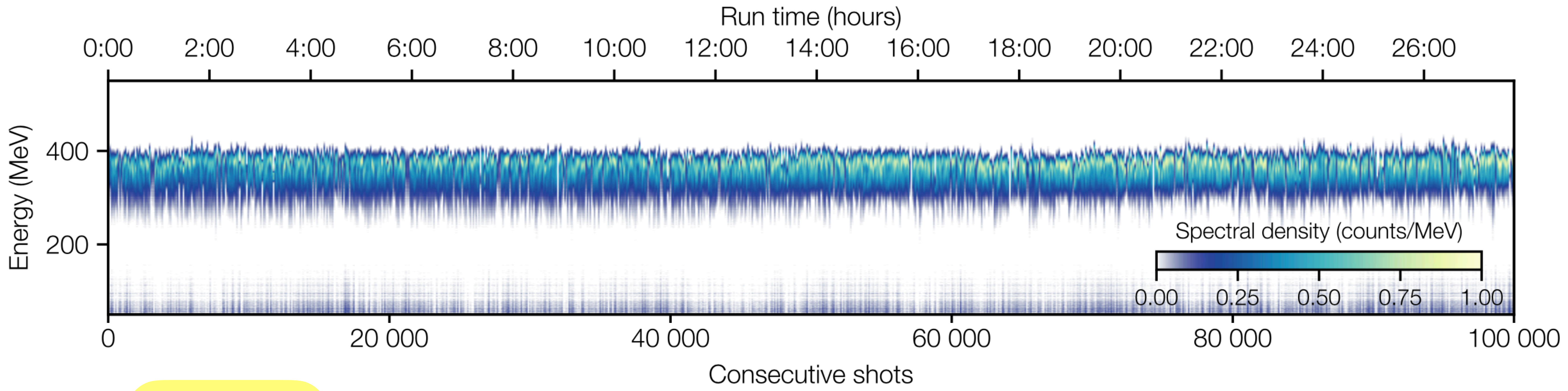
- Guiding of intense petawatt-class lasers: 62 pC at **6 GeV** has been demonstrated
- Research led by *Wim Leemans* (now at DESY)



LUX@DESY: enhanced energy spread and stability

- Energy spread optimization: **1.1%** (mad) → *M. Kirchen, et al. Phys. Rev. Lett. 126, 174801 (2021)*
- 24 hours run:100 000 consecutive electron beams → *A. Maier et al., Phys. Rev. X 10, 031039 (2020)*
- Prospects of enhanced control and stability through active feedback powered by AI.

1% beam energy stability is to be expected with moderate improvements to the laser stability



1.8 % energy jitter

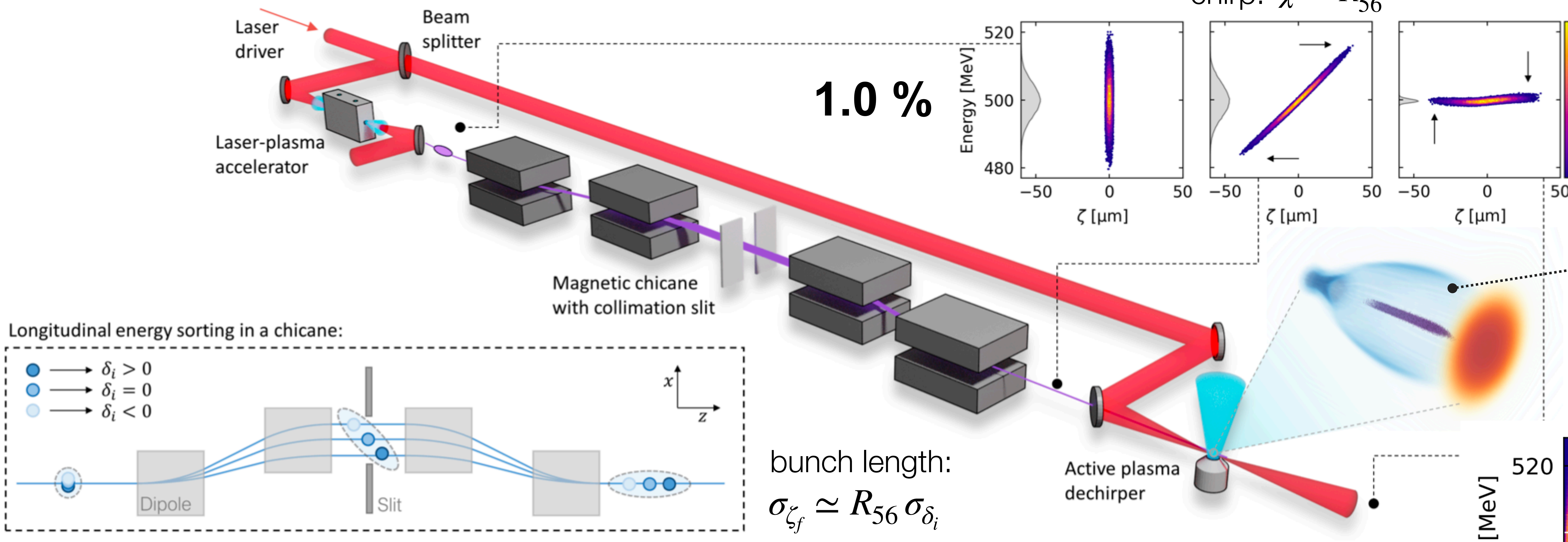
Energy Compression and Stabilization of Laser-Plasma Accelerators

A. Ferran Pousa et al. Physical Review Letters 129, 094801 (2022)

chirp: $\chi \simeq R_{56}^{-1}$

1.0 %

0.1 %



bunch length: $\sigma_{\zeta_f} \simeq R_{56}\,\sigma_{\delta_i}$

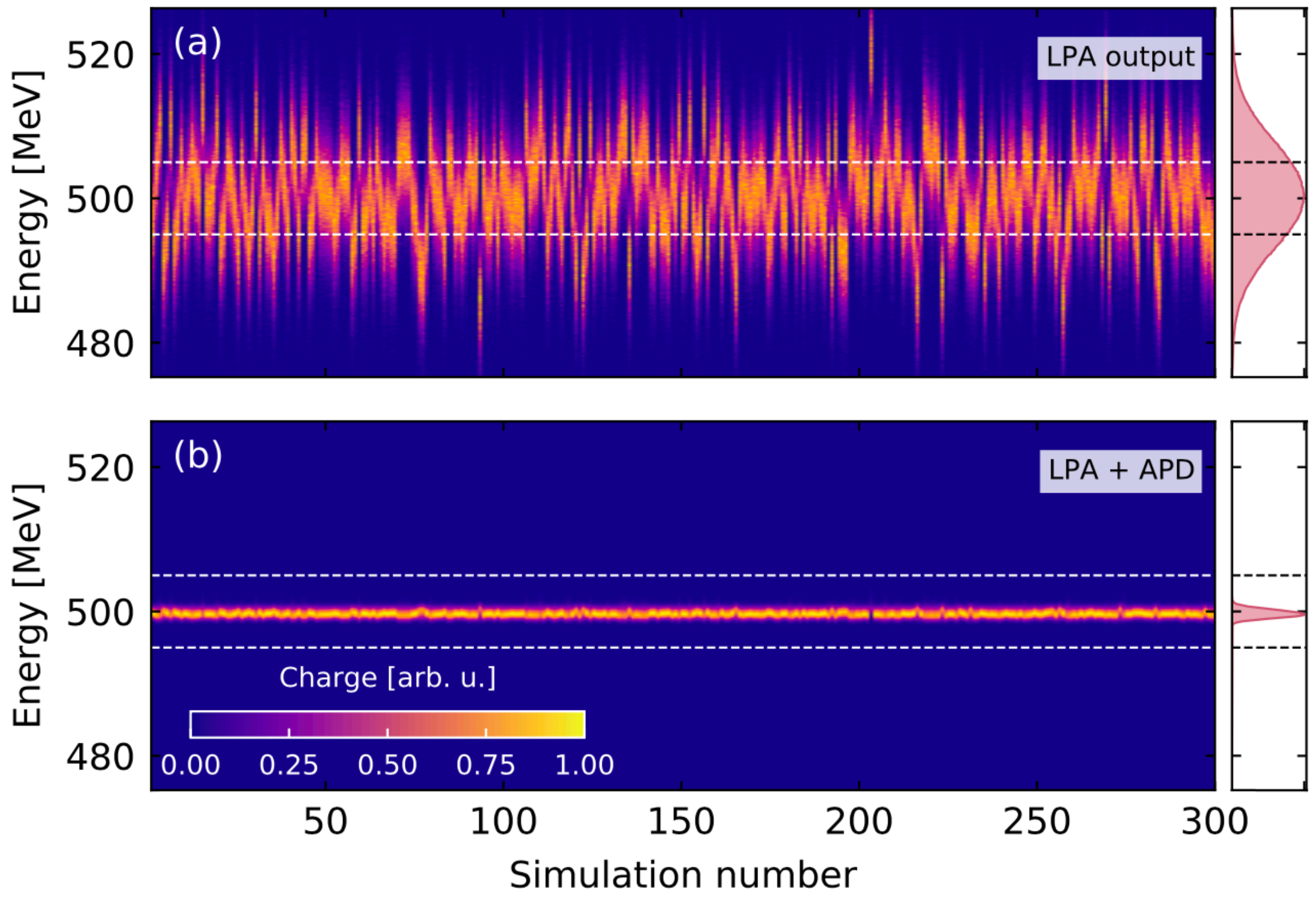
final energy spread:

$$\sigma_{\delta_f} = \frac{\sigma_{\zeta_i}}{R_{56}} \simeq \frac{\sigma_{\delta_i}}{S}$$

dechirping strength:

$$eE_{z,0}k_pL = E_{\mathrm{ref}}/R_{56}$$

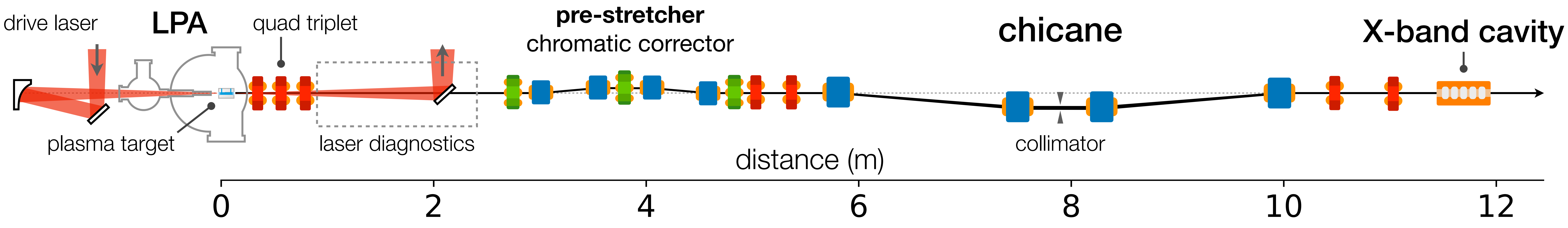
bunches before and after



- Compress the energy spread and jitter of a 1% beam down to the per-mille and sub-per-mille level, respectively.
- Using a active plasma dechirper enables kA-level peak currents for FEL operation with improved performance and stability.

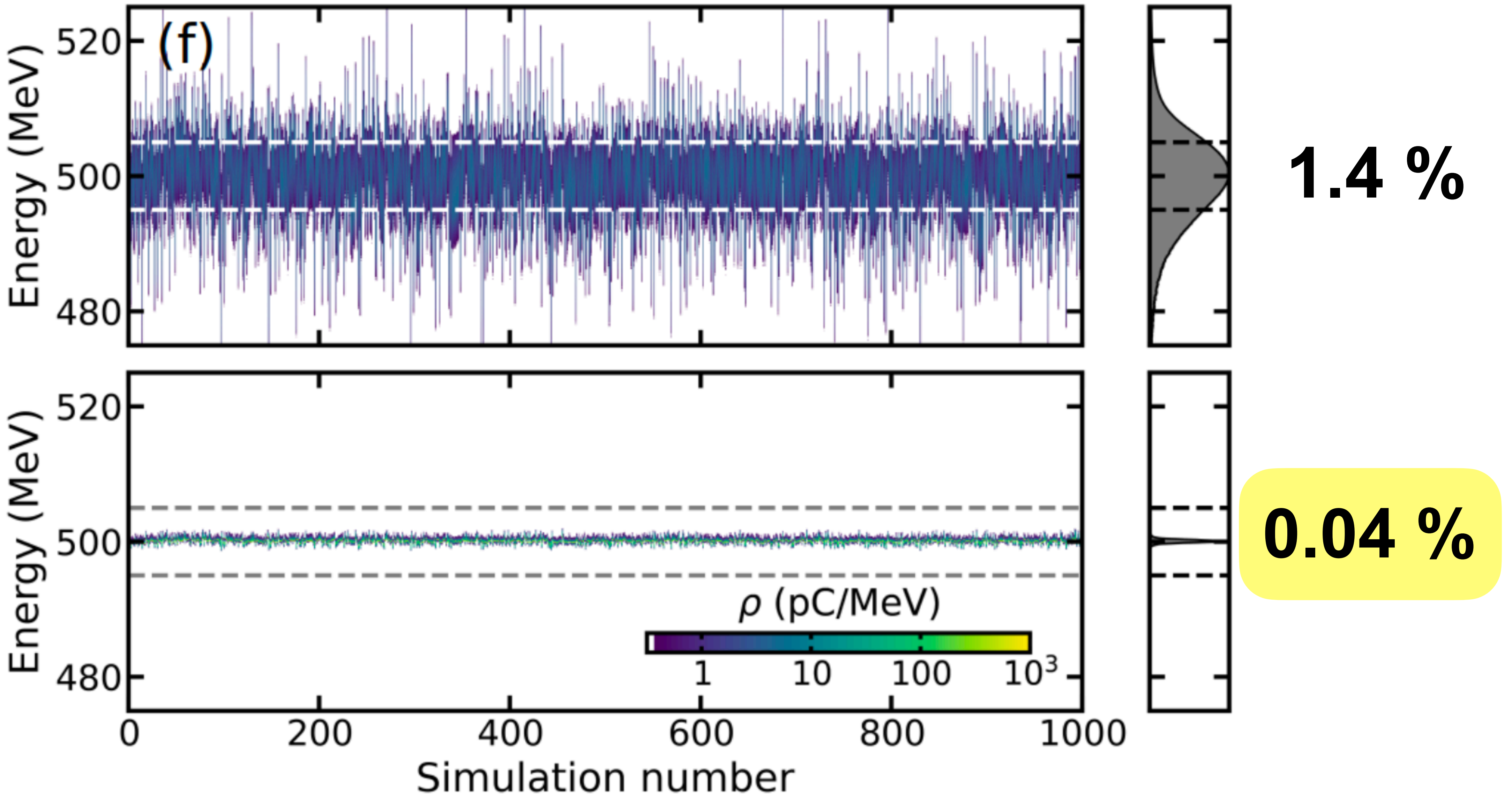
Design of a prototype laser-plasma injector for an electron synchrotron

S. A. Antipov et al. Physical Review Accelerators and Beams 24, 111301 (2021)



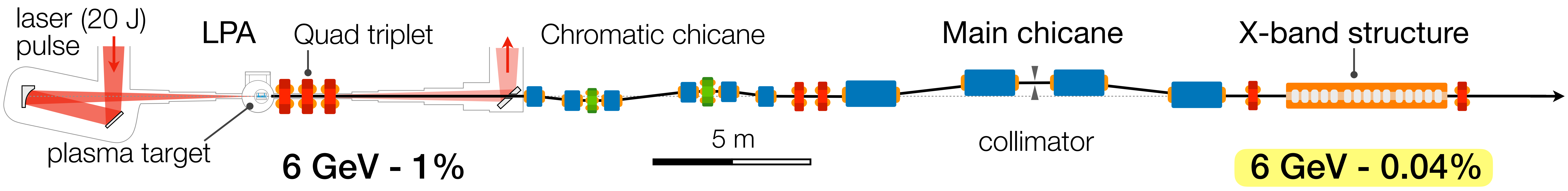
Prototype injector with X-band energy compression

- 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.



The Plasma Injector for PETRA IV: conceptual design

Maximizes charge injection throughput and stability



Laser Plasma Accelerator (LPA)

- **Drive Laser (Ti:Sa | λ_0=800 nm):**
  Peak power: ~350 TW, energy: ~20 J.
- **Plasma source (~20 cm):**
  Controlled injection (LUX).
  Efficient laser guiding (HOFI).
- **Bayesian optimization:**
  maximizes the beam spectral density
  at 6 GeV and minimizes the laser energy.

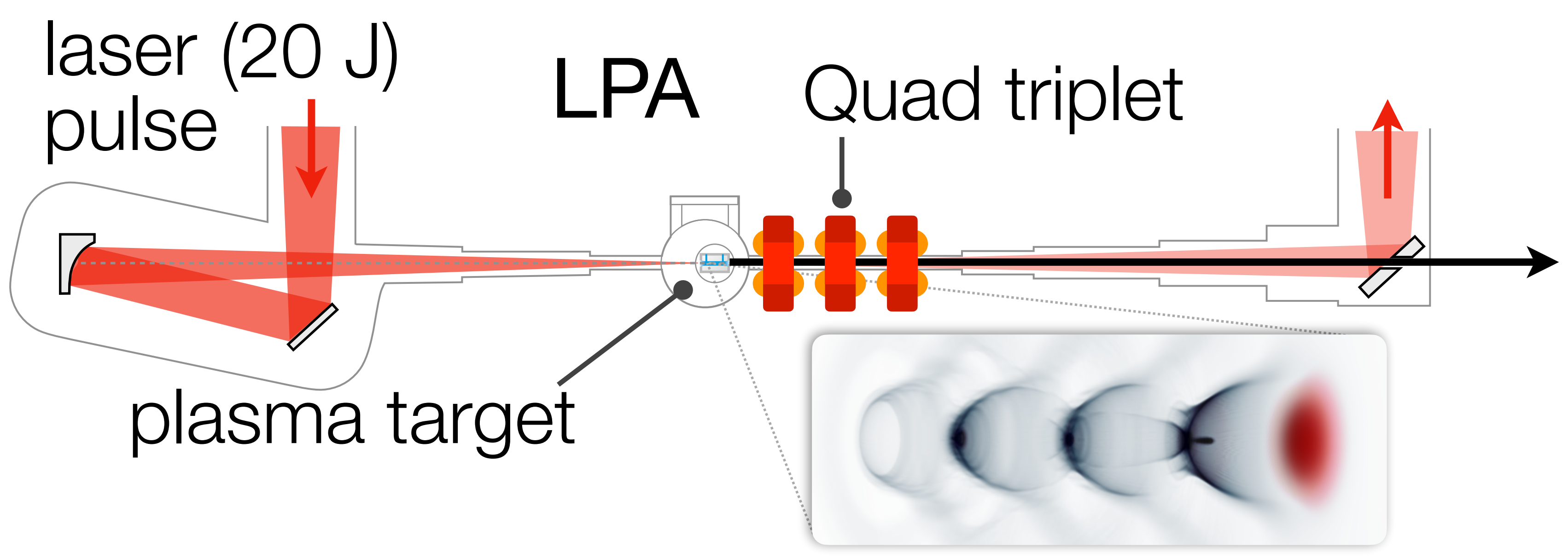
Energy Compression Beamline (ECB)

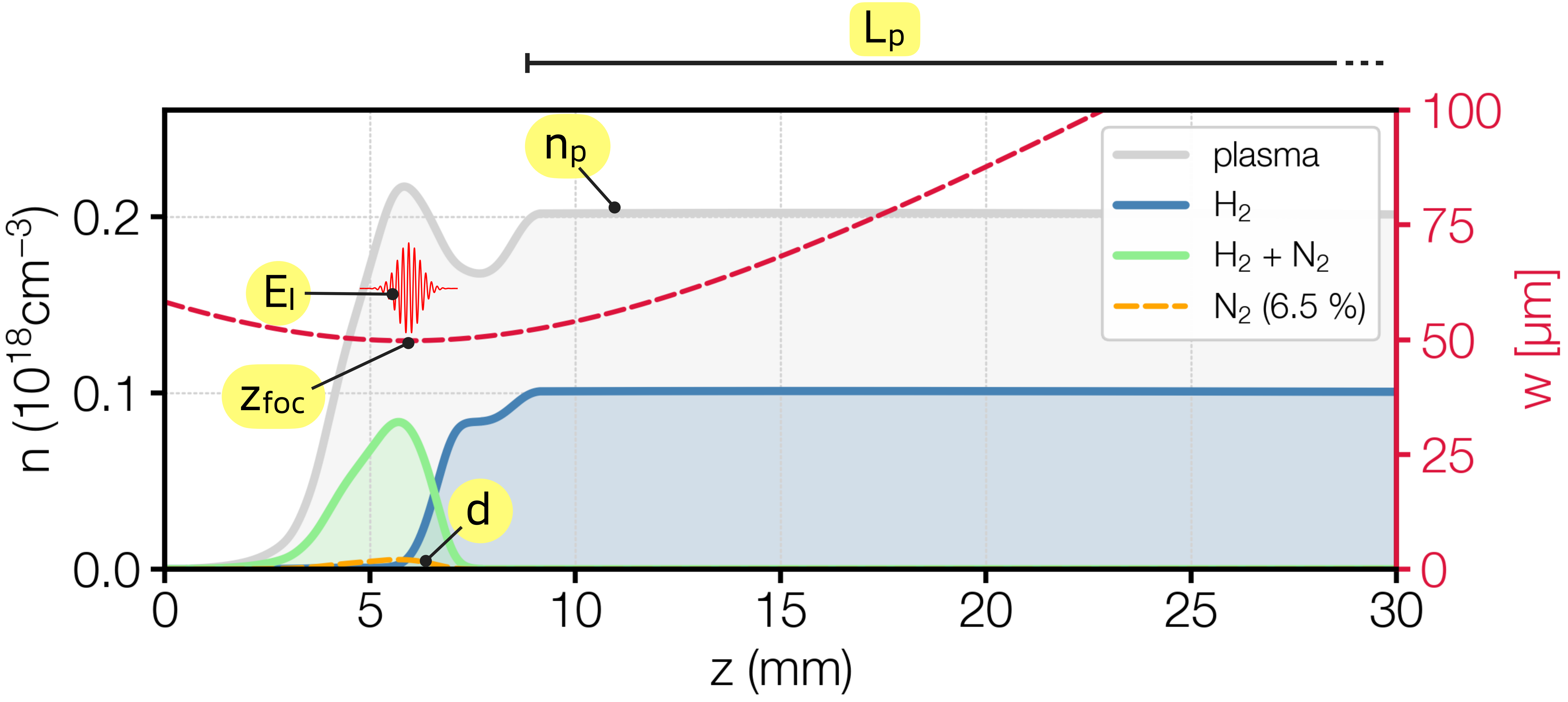
- **Quad triplet:** Beam capturing
- **Chromatic chicane:** pre-stretcher + chromaticity correction (horizontal plane)
- **Main chicane:** beam length decompression
- **X-band structure:** energy compression and stabilization

Enables sub-per-mile level of energy spread and stability

The Plasma Injector: LPA optimization at 6 GeV

Bayesian optimization [1] with FBPIC [2] and Optimas [3]





- **LUX-like plasma profile:**
  with HOFI channel (w_m = 50 μm)
  - Variable density. (~ 2 × 10^{17} cm^{-3})
  - Variable dopant concentration.
  - Variable plateau length.
- **Laser pulse (flattened Gaussian N = 100)**
  w0 = 50 μm, τ = 53.3 fs.
  - Variable energy.
  - Variable focal position.

- **Score function definition:**
  - goal momentum: $\mathrm{p_{z,0}} = 6\ \mathrm{GeV/c}$
  - average deviation: $\hat{\sigma}^2_{\mathrm{p_{z,0}}} = \hat{\sigma}^2_{\mathrm{p_z}} + (\bar{\mathrm{p}}_\mathrm{z}/\mathrm{p_{z,0}} - 1)^2$
  - score function: $\mathrm{f} = -\sqrt{\mathrm{Q}}/\hat{\sigma}_{\mathrm{p_{z,0}}}/\mathrm{E}^2_{\mathrm{laser}}$

[1] S. Jalas et al. Phys. Rev. Lett. 126, 104801 (2021)
[2] R. Lehe et al. Comp. Phys. Comm. 203, 66 (2016)
[3] A. Ferran Pousa et al. Phys. Rev. Accel. Beams 26, 084601 (2023)

The Plasma Injector: LPA optimization at 6 GeV

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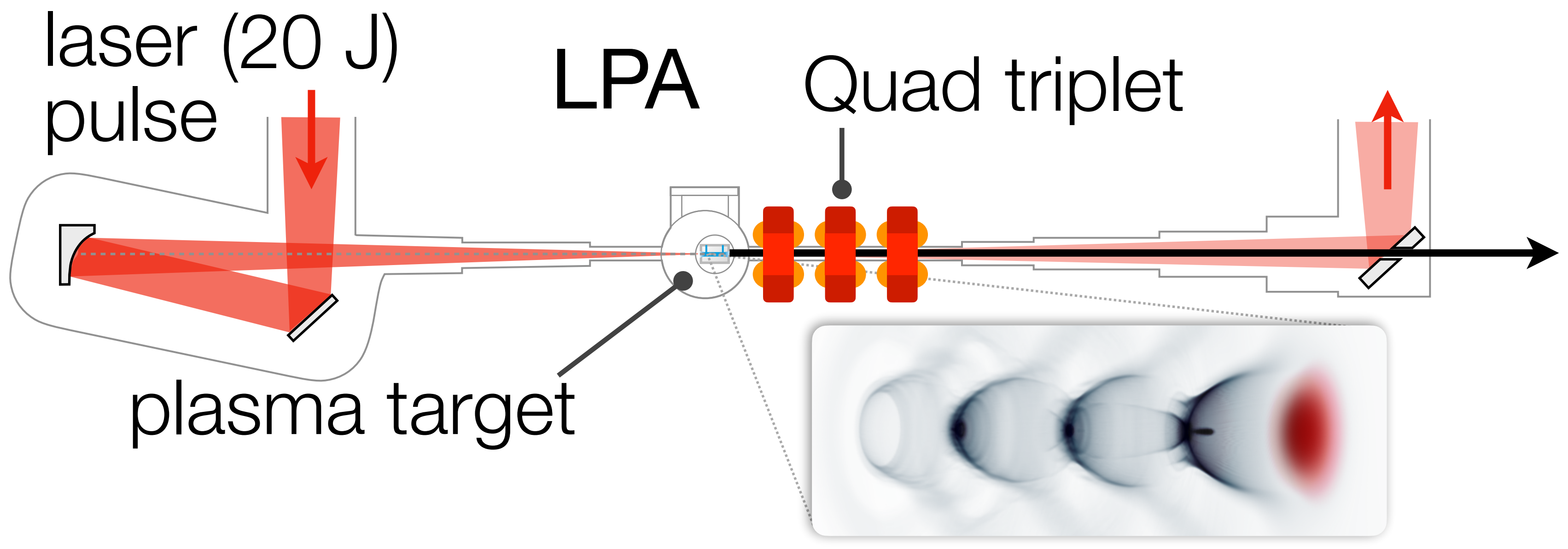

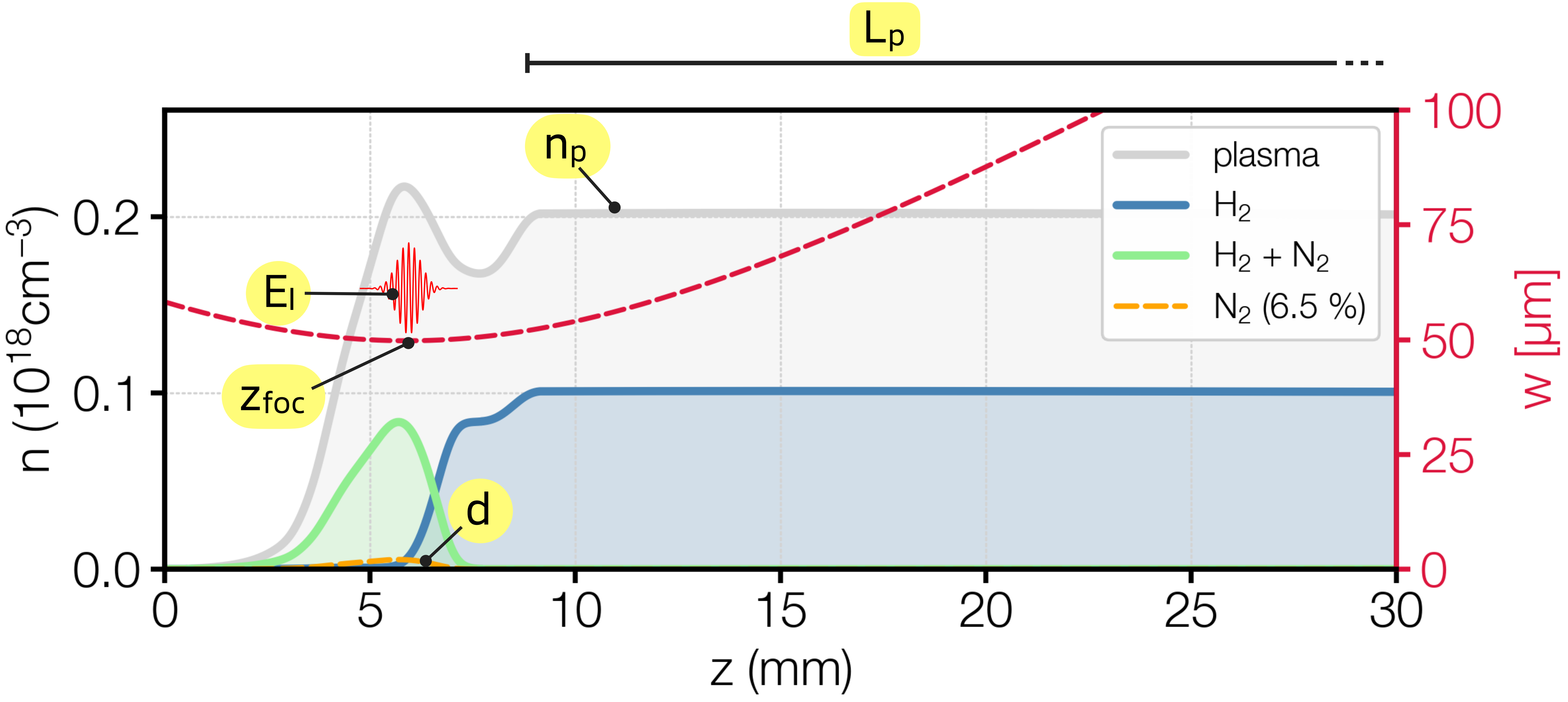

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- **Laser pulse (flattened Gaussian N = 100)**
  w0 = 50 μm, τ = 53.3 fs.
  - Variable energy.
  - Variable focal position.

- **Score function definition:**

  Optimize for beams with narrow and dense spectrum peaking at 6 GeV, favoring a reduced laser energy.

[1] S. Jalas et al. Phys. Rev. Lett. 126, 104801 (2021)
[2] R. Lehe et al. Comp. Phys. Comm. 203, 66 (2016)
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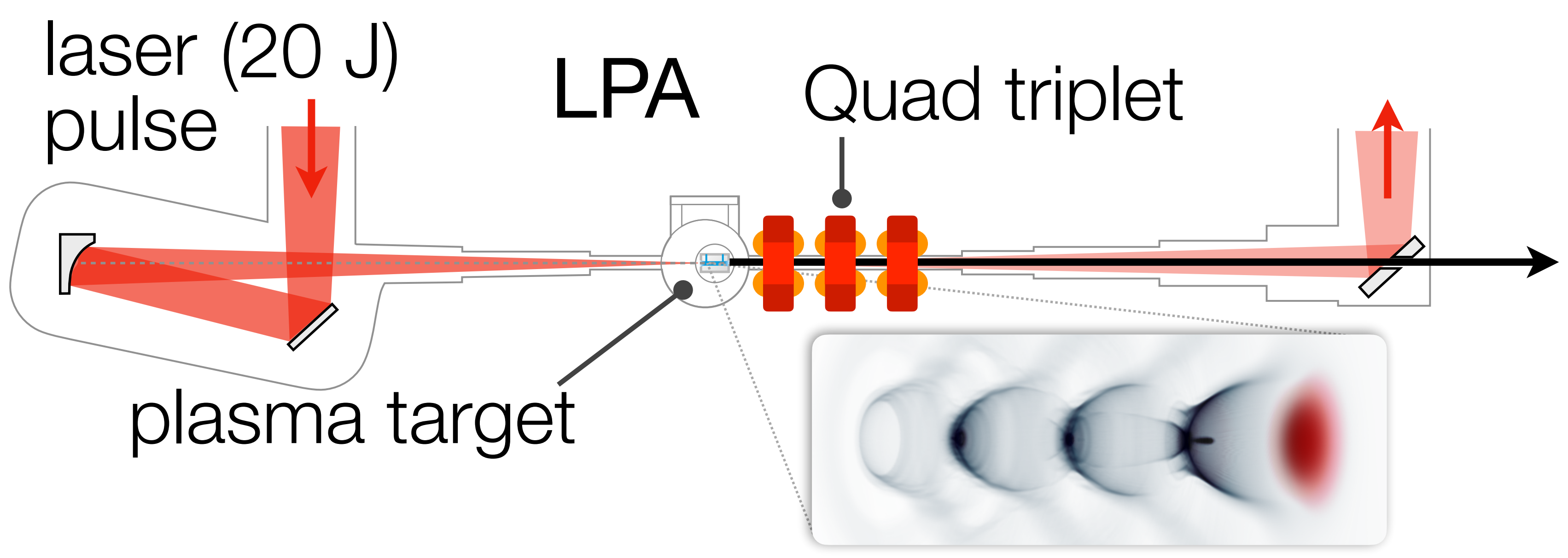
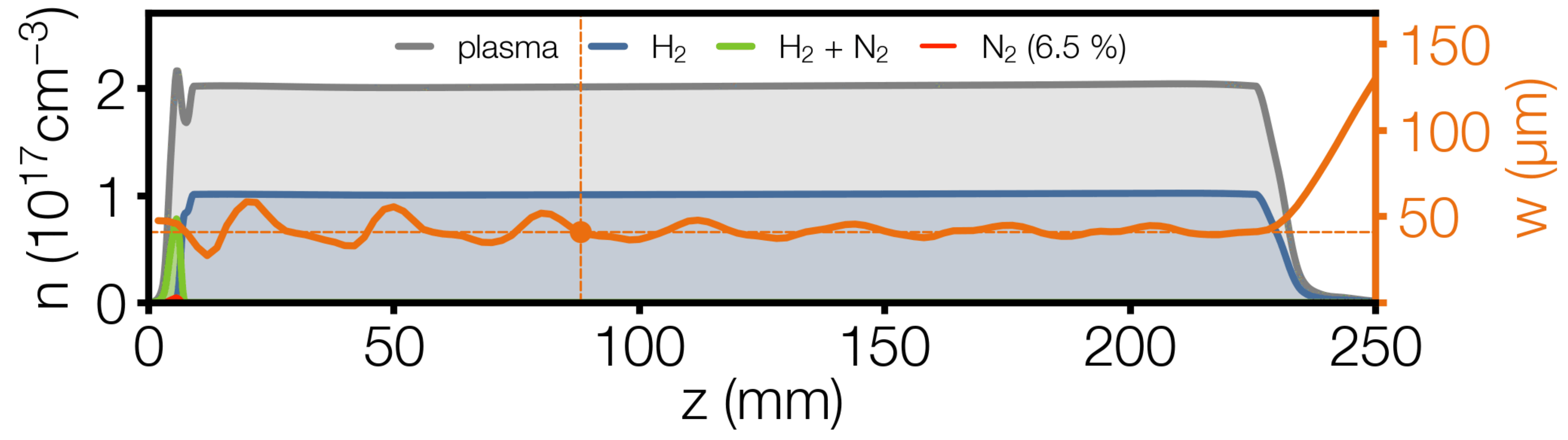
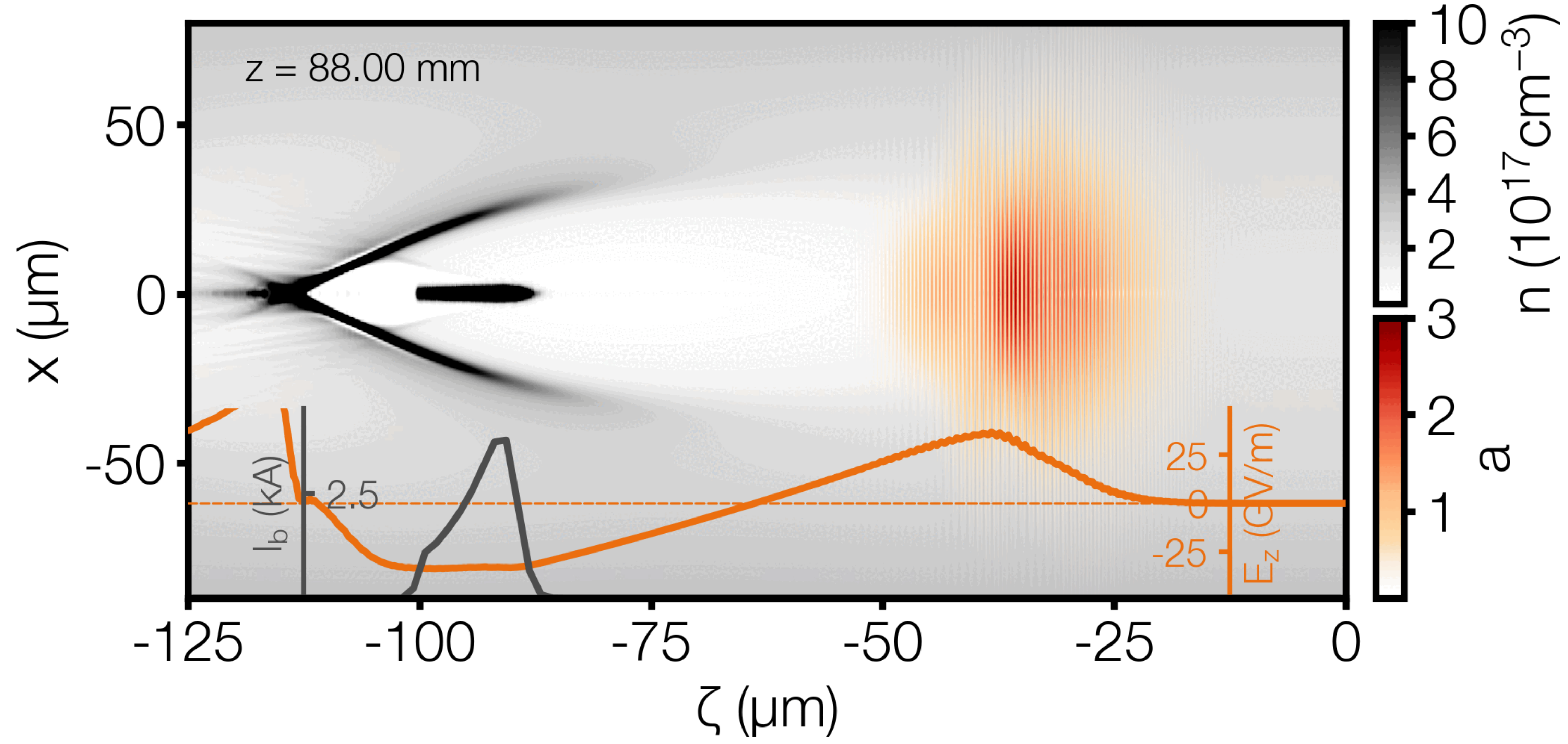
The Plasma Injector: LPA optimization at 6 GeV

Working point 1: optimal case for 50 μm guiding channel







Laser pulse

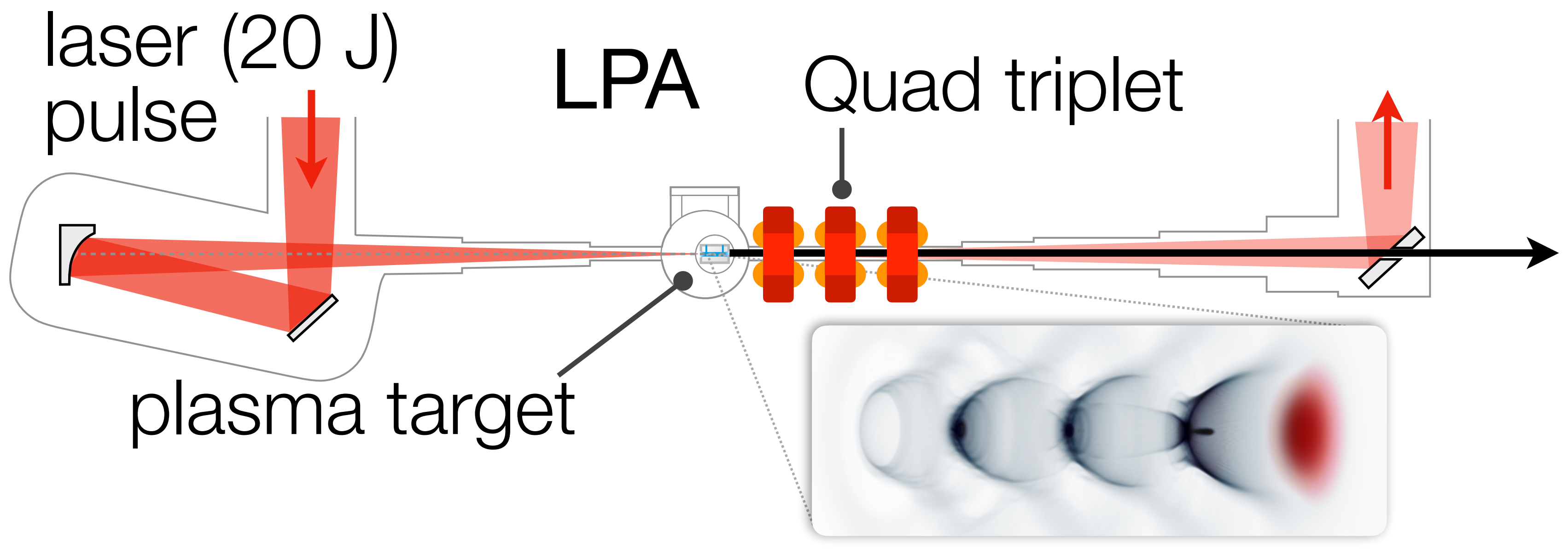
- Realistic profile: Flattened Gaussian $a_0 = 2.02$, $w_0 = 50$ μm, $P_0 = 345$ TW, τ= 53 fs (fwhm), Energy = 19.6 J.
- Focal length = 8.8 m.

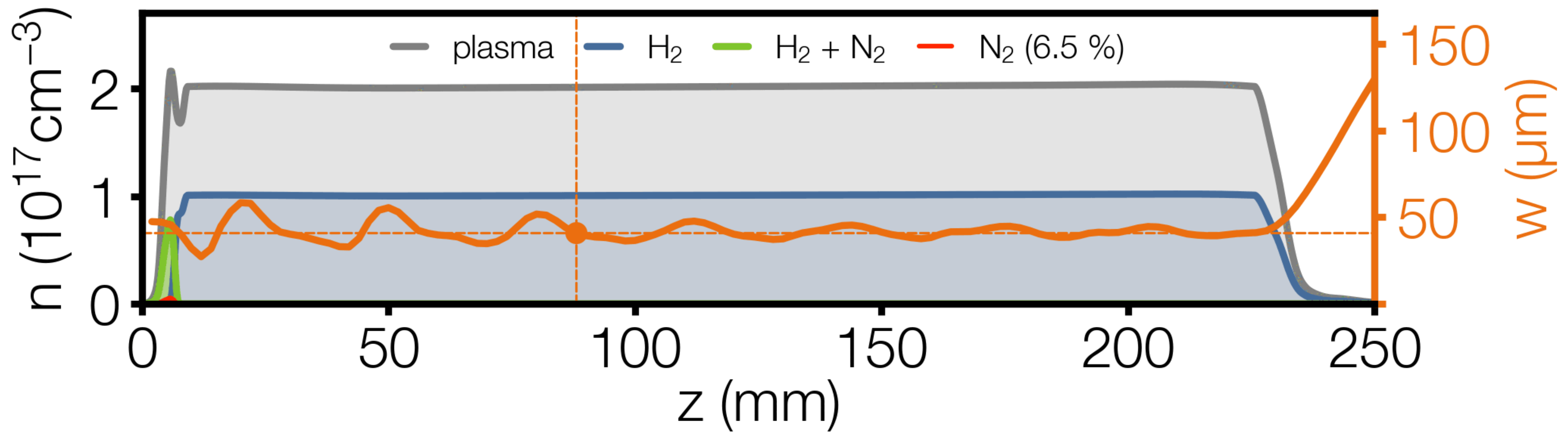
Plasma target

- LUX-type profile: $n_p = 2.02 \times 10^{17}$ cm^{-3}, plateau length: 22 cm.
- Transversely parabolic profile with $w_M = 50$ μm,. (HOFI compatible)

The Plasma Injector: LPA optimization at 6 GeV

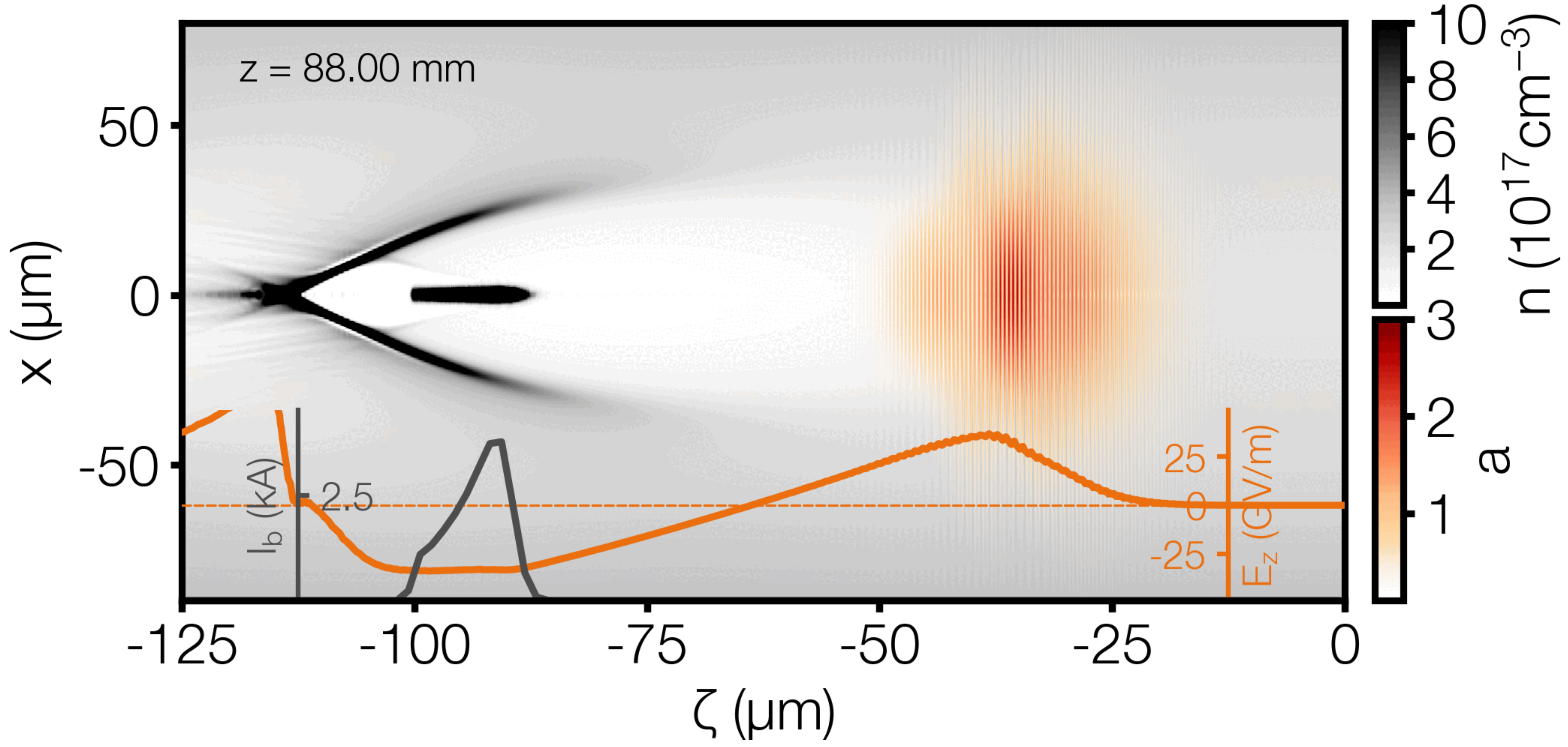
Working point 1: optimal case for 50 µm guiding channel





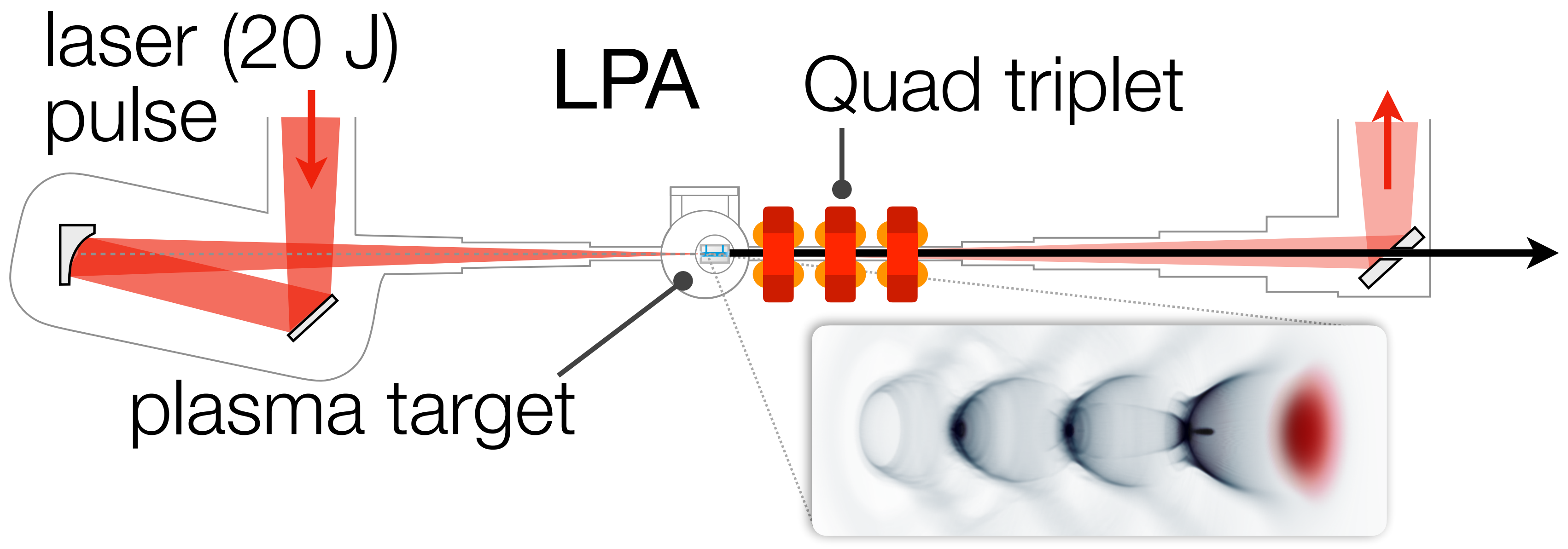
Laser and Wakefield evolution

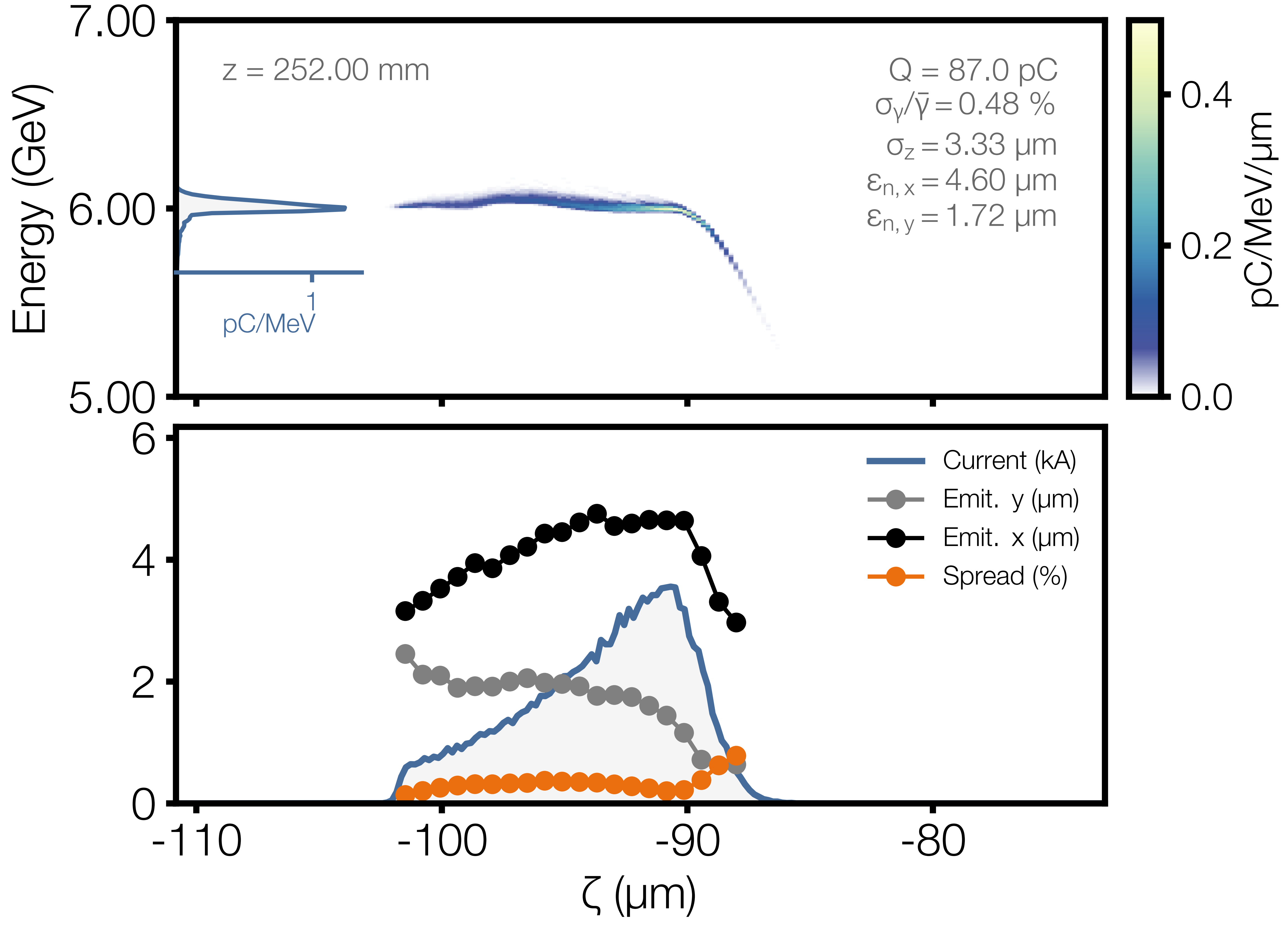
- Drive laser dynamics: damped oscillations, pulse edging, power amplification, depletion and dephasing.
- Evolving wakefield ➟ average beam-loading



The Plasma Injector: LPA optimization at 6 GeV

Working point 1: optimal case for 50 μm guiding channel



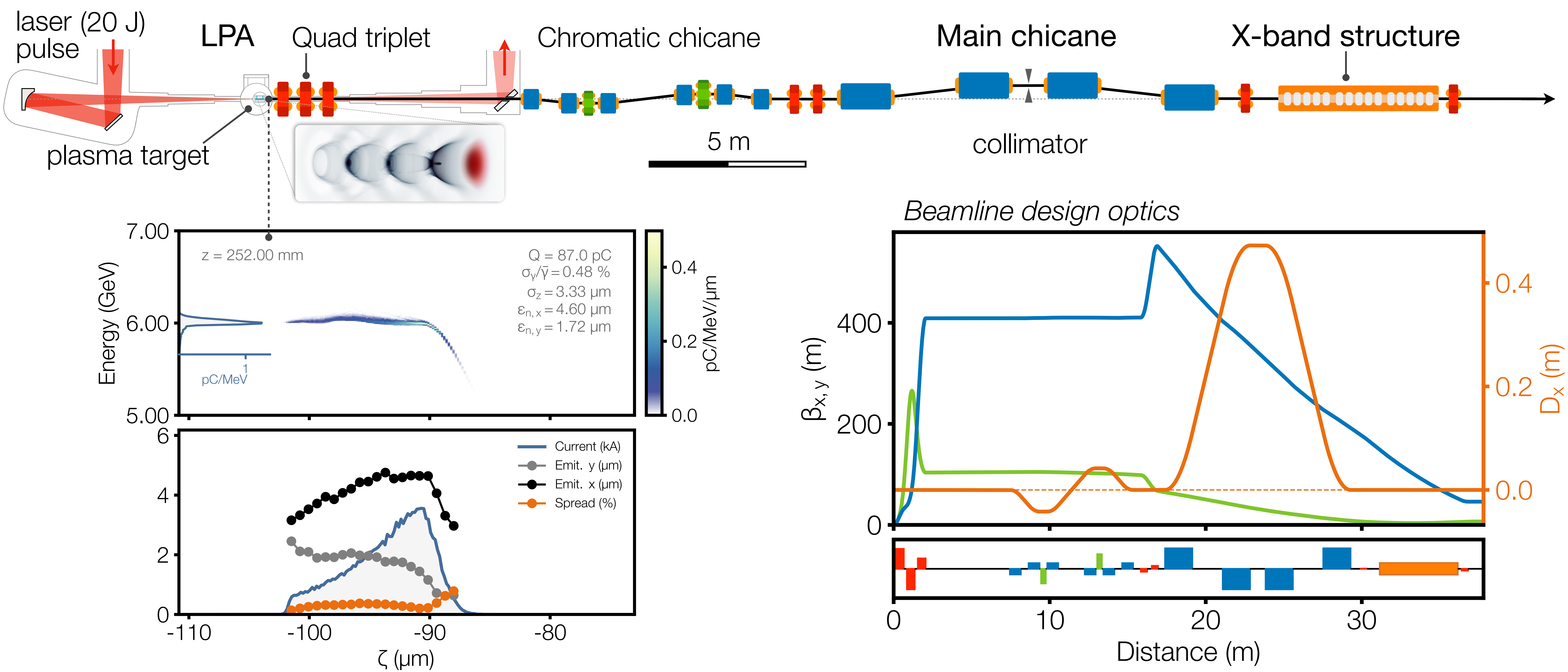


Electron beam

- Optimization: averaged beam-loading (no chirp).
- Charge: 87 pC, Energy spread: 0.5 %.
- Norm. emittance: 4.6 μm and 1.7 μm.
- Divergence: 0.22 mrad and 0.12 mrad.
- Efficiency: 2.7 %

The Plasma Injector: beamline simulation

Working point 1: beamline simulation (ocelot)



The Plasma Injector: beamline simulation

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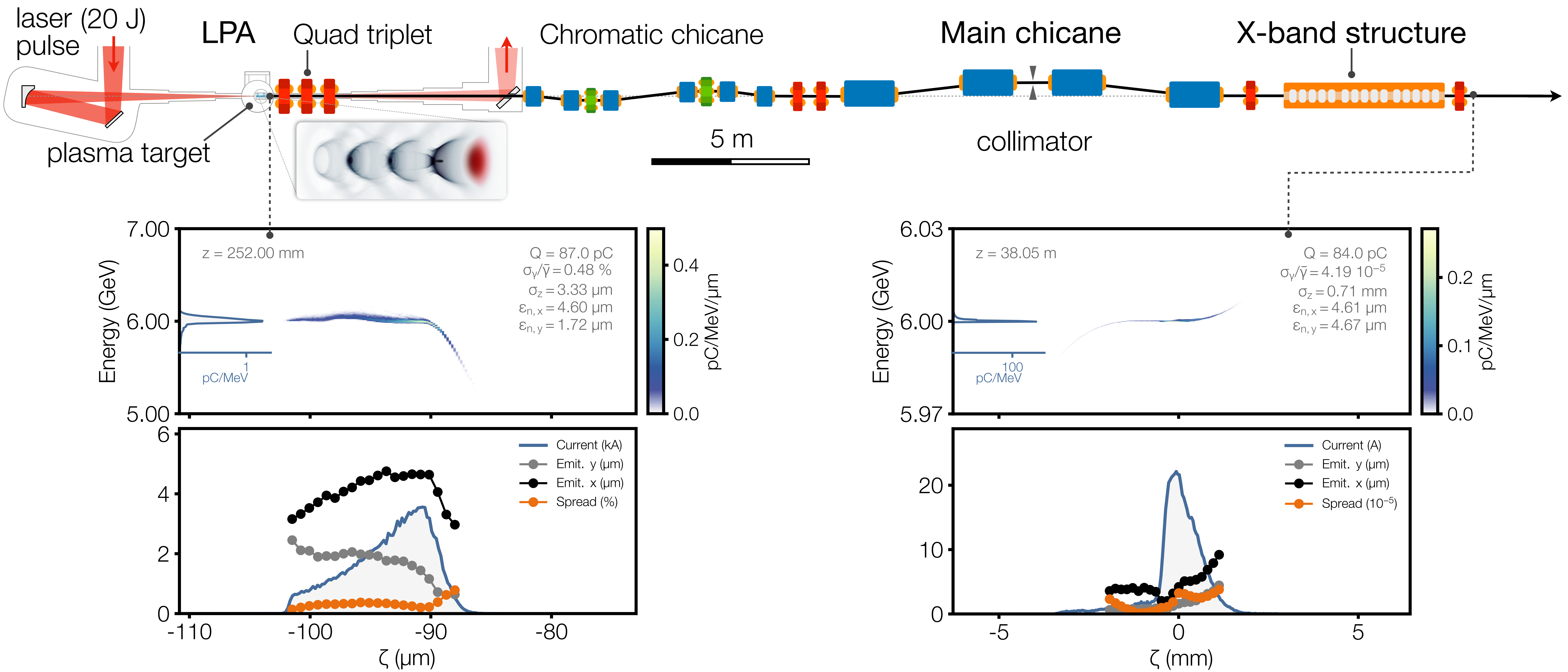

The Plasma Injector: beamline simulation

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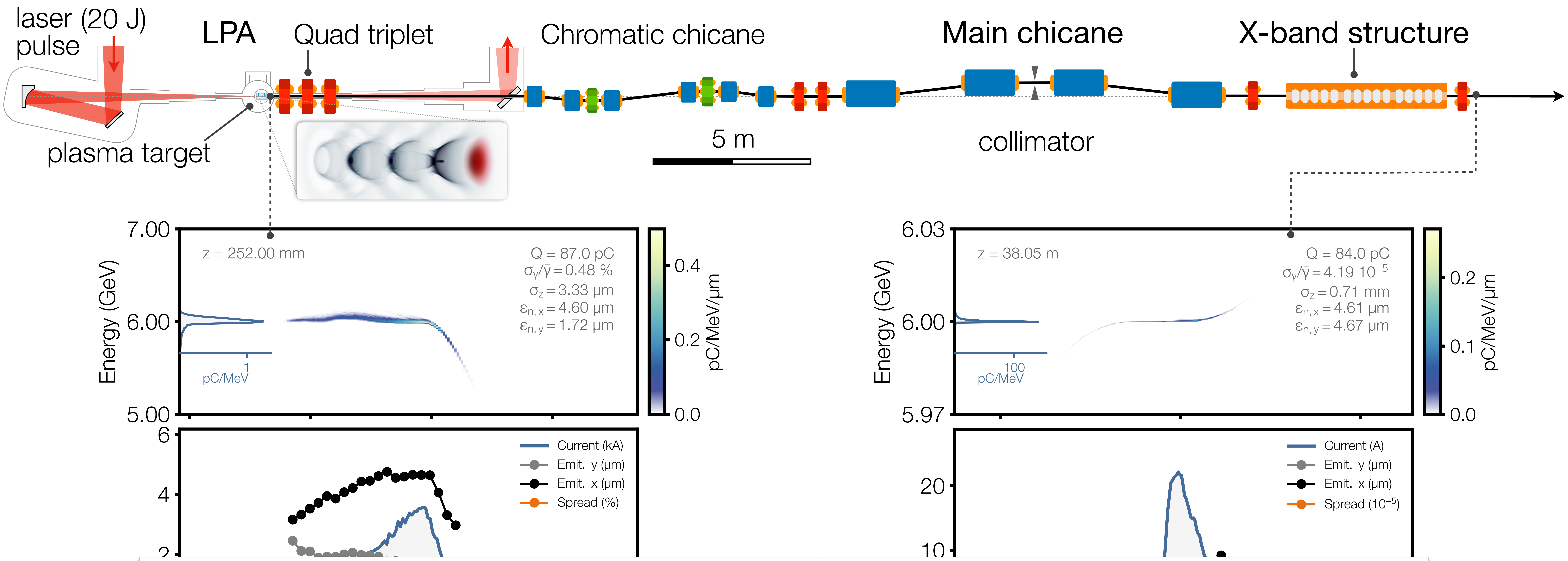


About two orders of magnitude reduction of the energy spread ➟ $\sigma_\gamma/\bar{\gamma} = 0.004\ \%$

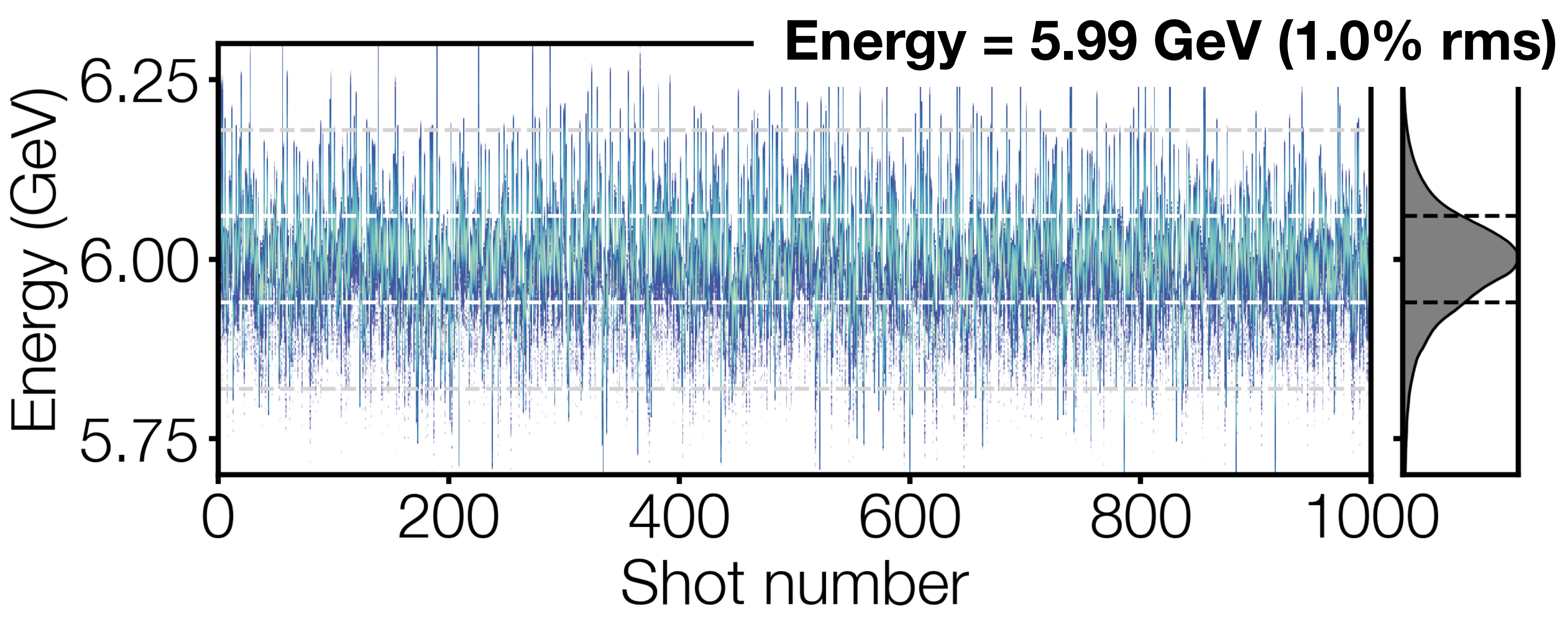
Emittance is preserved in the horizontal plane (chromatic correction)

Surrogate modeling of key beam parameters

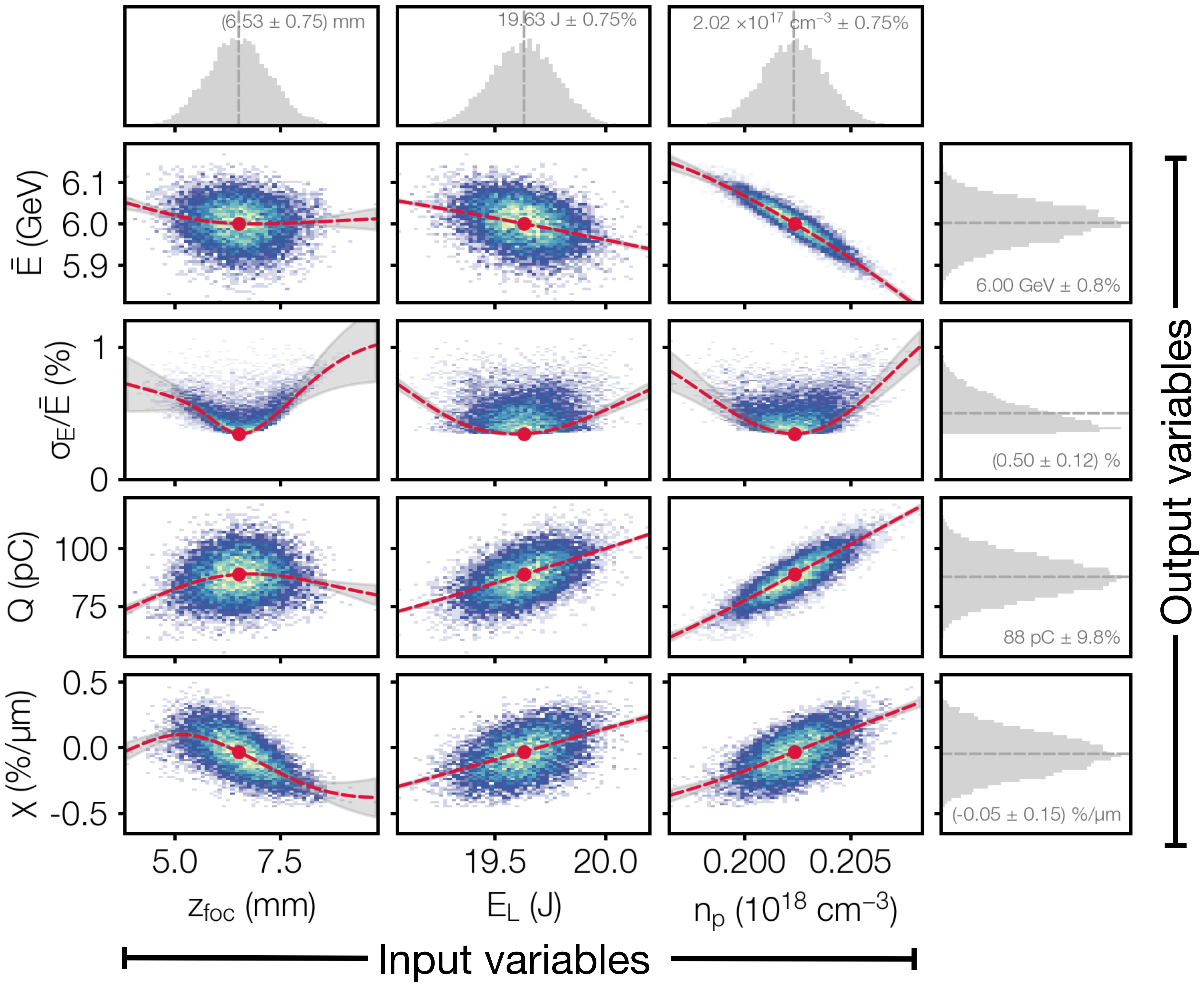
Modeling beam response to jitters for S2E simulation studies

Jitter and tolerance analysis

- Evaluate the combined influence of laser and plasma jitter on the beam parameters.
- Gaussian process models trained with 500 simulations sampled around working point.
- Varying parameters: Focus position, laser energy & plasma density.
- Allows us to define required laser and target stability to reach desired LPA performance.

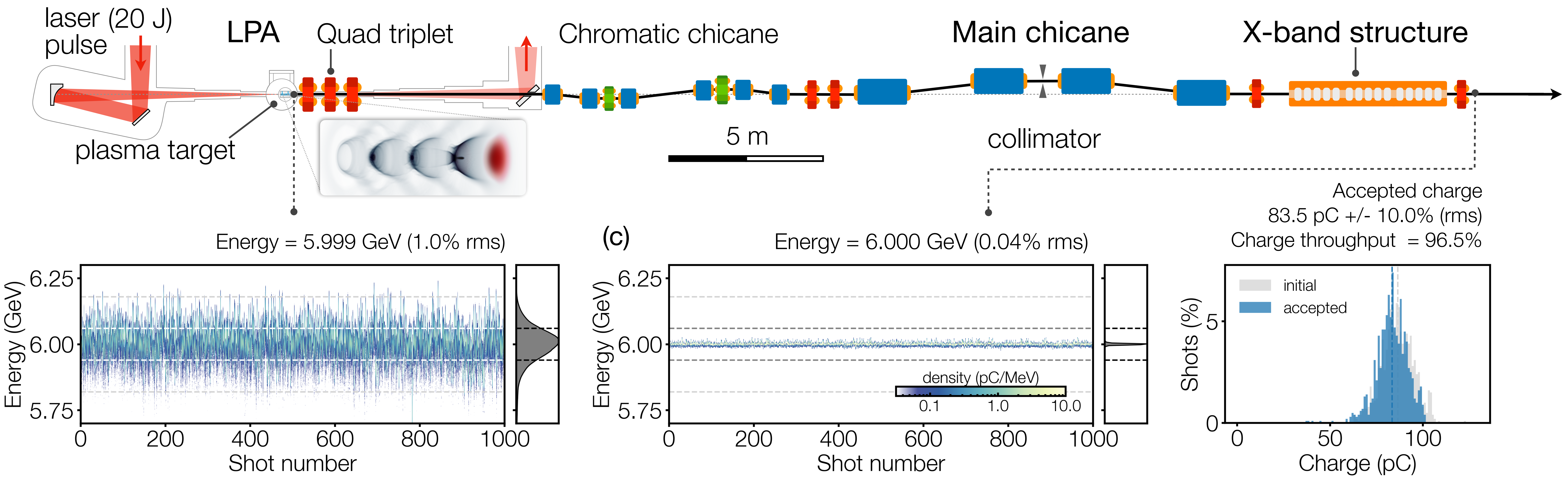


Jitters : {0.75 mm in z_{foc}, 0.75% in E_L , 0.75% in n_p}



The Plasma Injector: simulation framework

Start-to-end simulations with realistic jitter

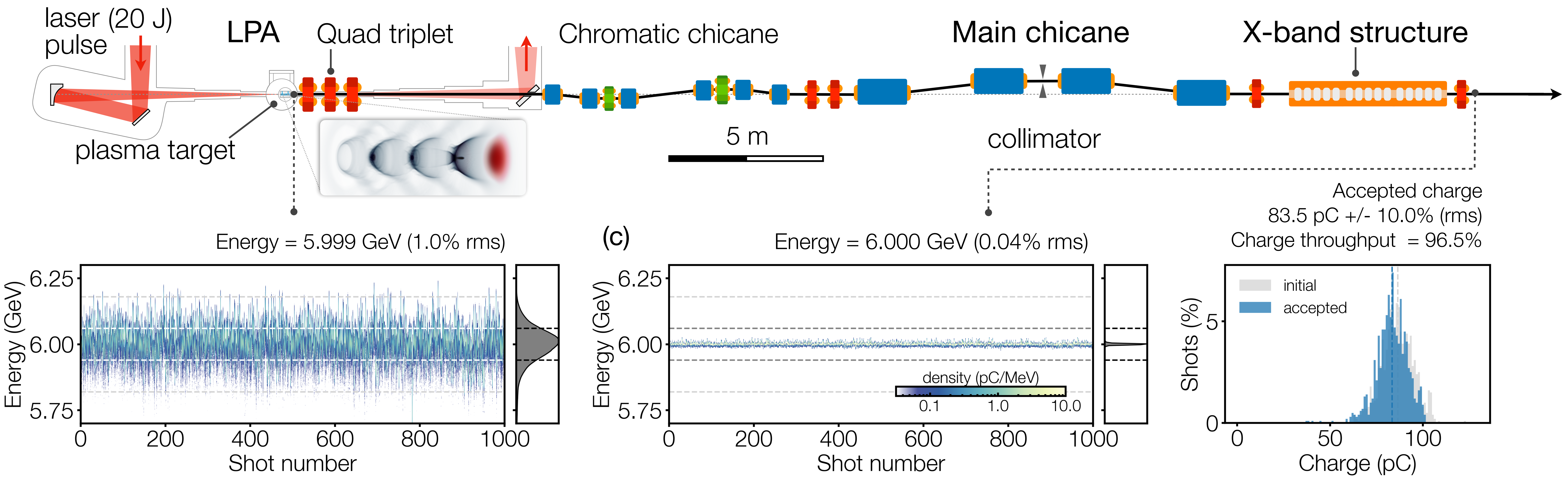


Jitters : {0.75 mm in z_f, 0.75% in E_L , 0.75% in n_p, **0.2 mrad in θ_x, 0.1 mrad in θ_y, 100 fs in RF timing**}

Introduced in FBPIC *Introduced in OCELOT*

The Plasma Injector: simulation framework

Start-to-end simulations with realistic jitter

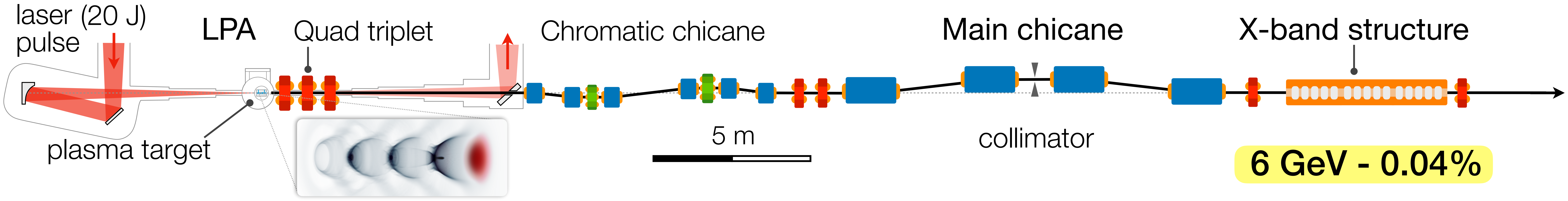


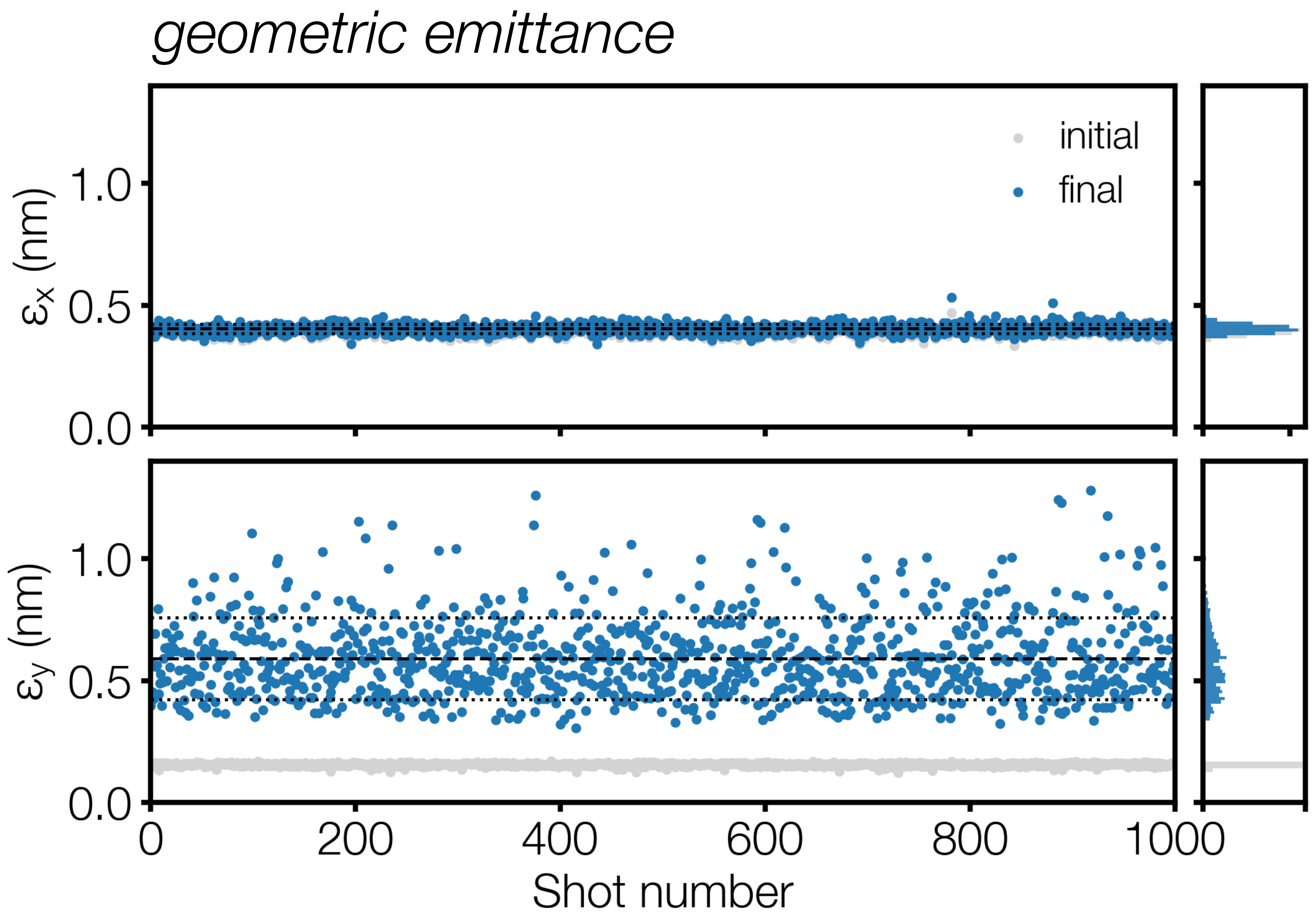
Jitte … RF timing}

Overall energy deviations reduced by factor 25 ➟ 0.04%
Emittance is preserved in the horizontal plane (chromatic correction)
Charge throughput 96.5%

The Plasma Injector: simulation framework

Start-to-end simulations with realistic jitter





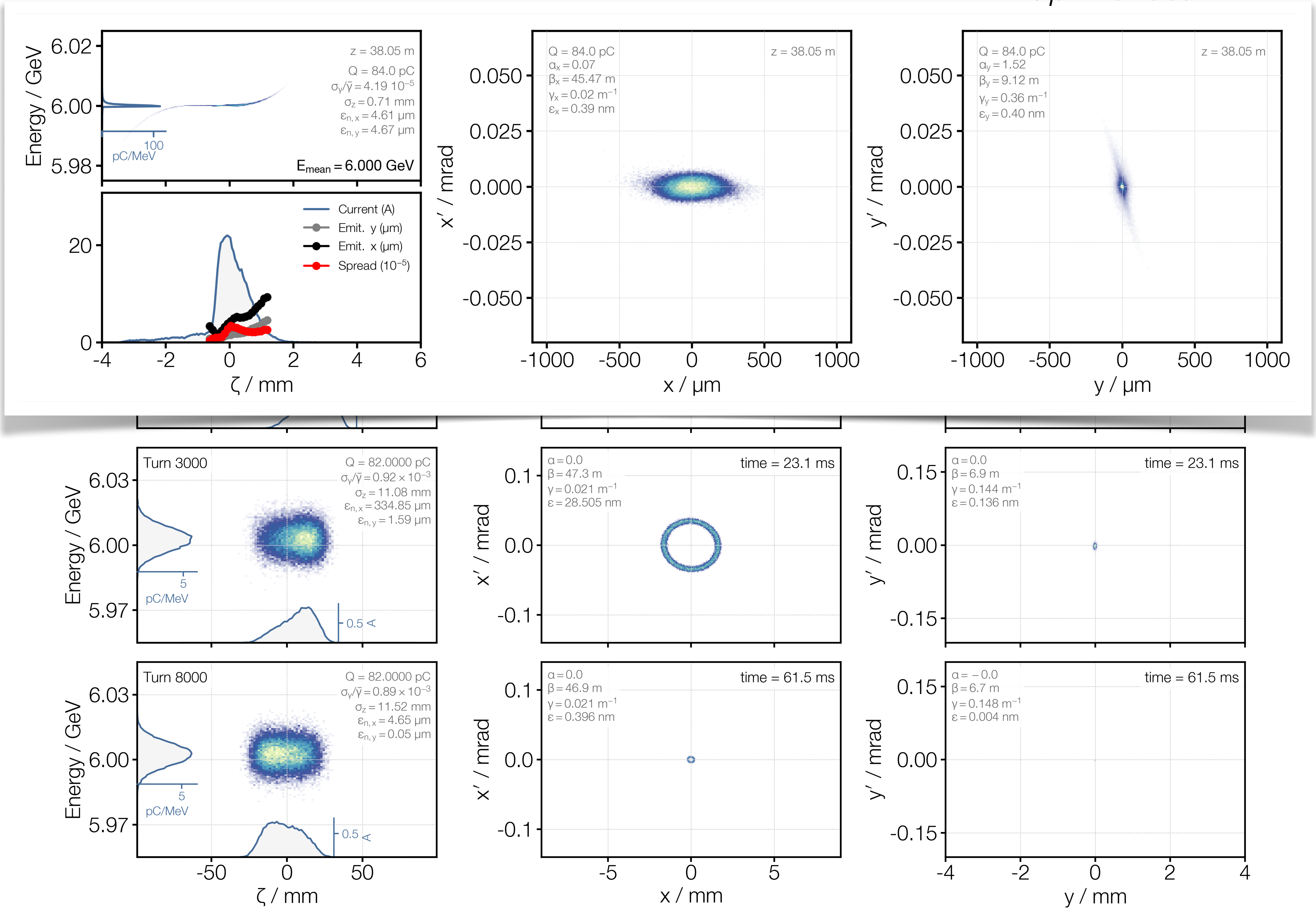
Collective beam parameters

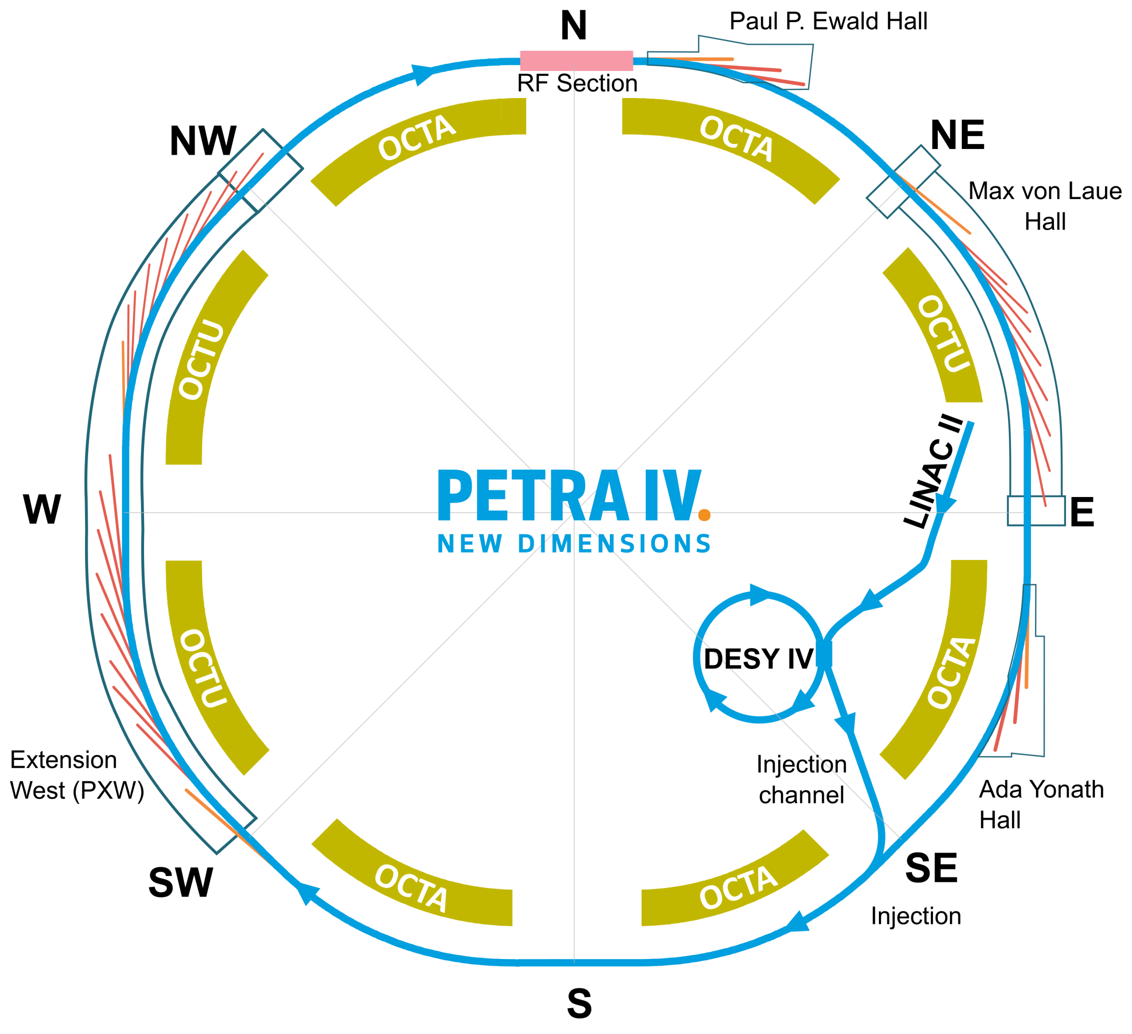
Parameter	After LPA	After ECB
Charge	87 pC	84 pC
Charge spread	9.8 %	10.0 %
Energy	5.999 GeV	6.000 GeV
Energy spread	1.0 %	0.04%
Emittance (x, y)	0.4, 0.2 nm	0.4, 0.6 nm

The Plasma Injector: injection into PETRA IV

PETRA IV tracking with ELEGANT

Optimal beam





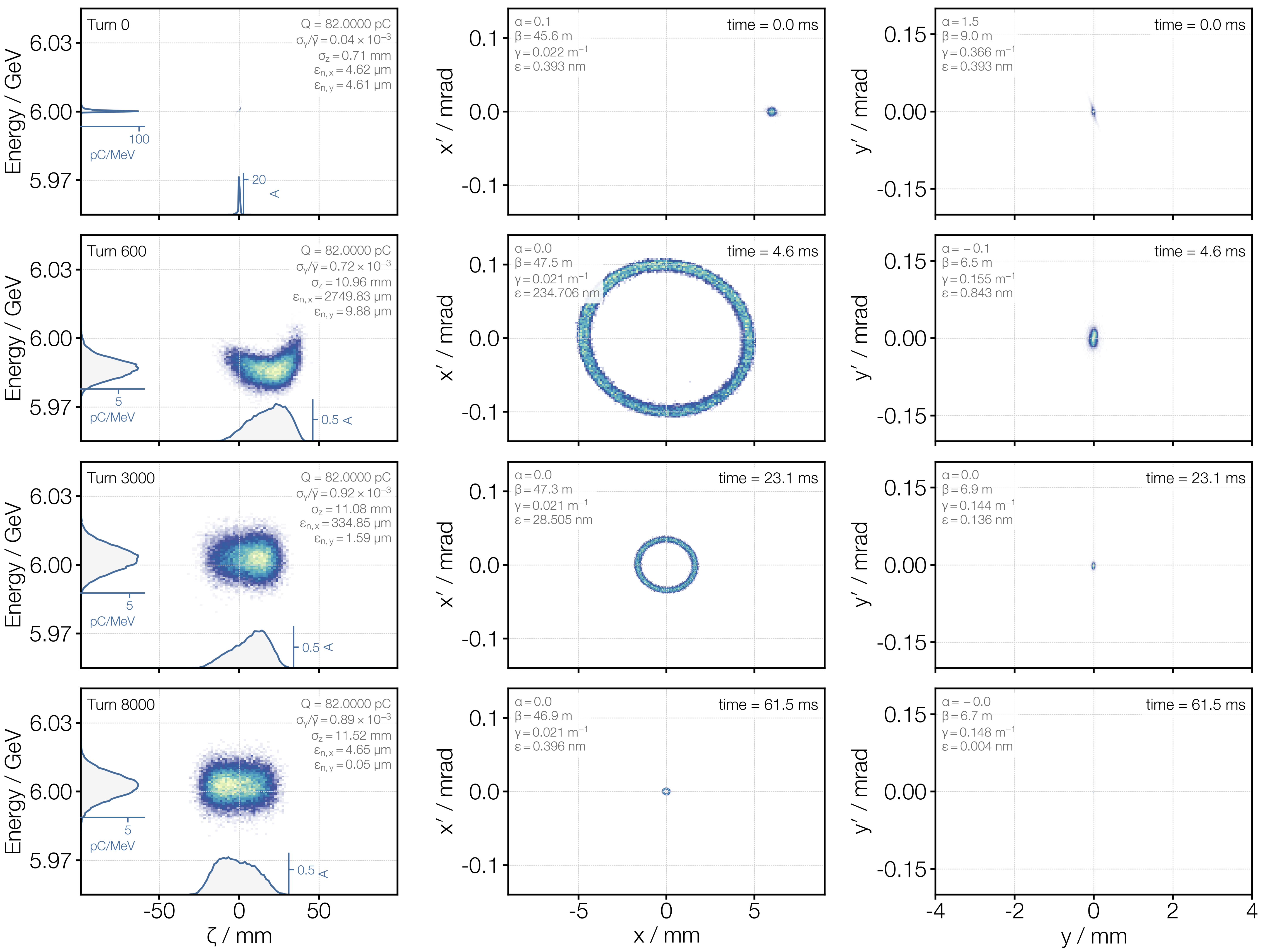
PETRA IV tracking — ELEGANT

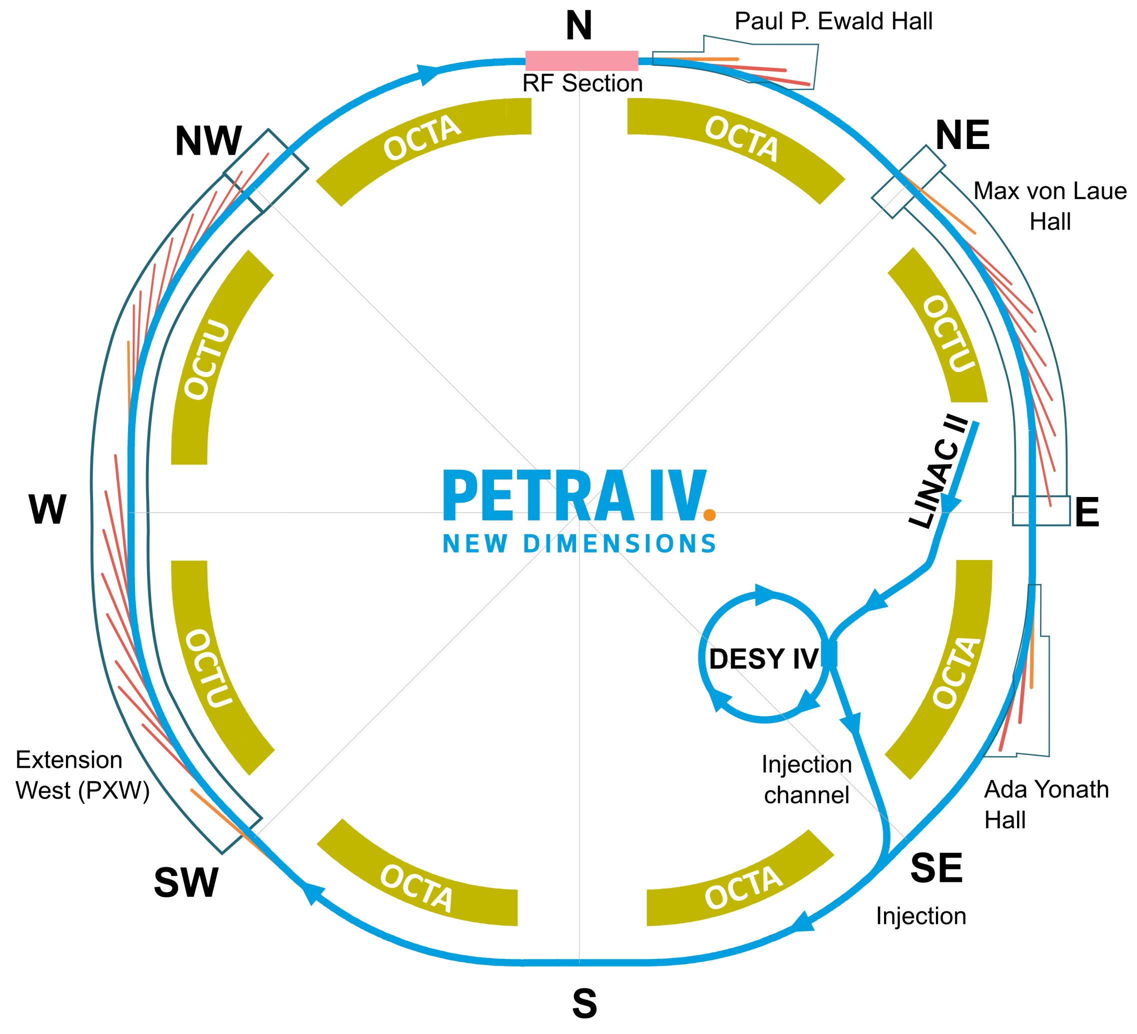
- Simulation for 8000 turns (3 x damping time)
- No particle losses.

The Plasma Injector: injection into PETRA IV

PETRA IV tracking with ELEGANT

Optimal beam





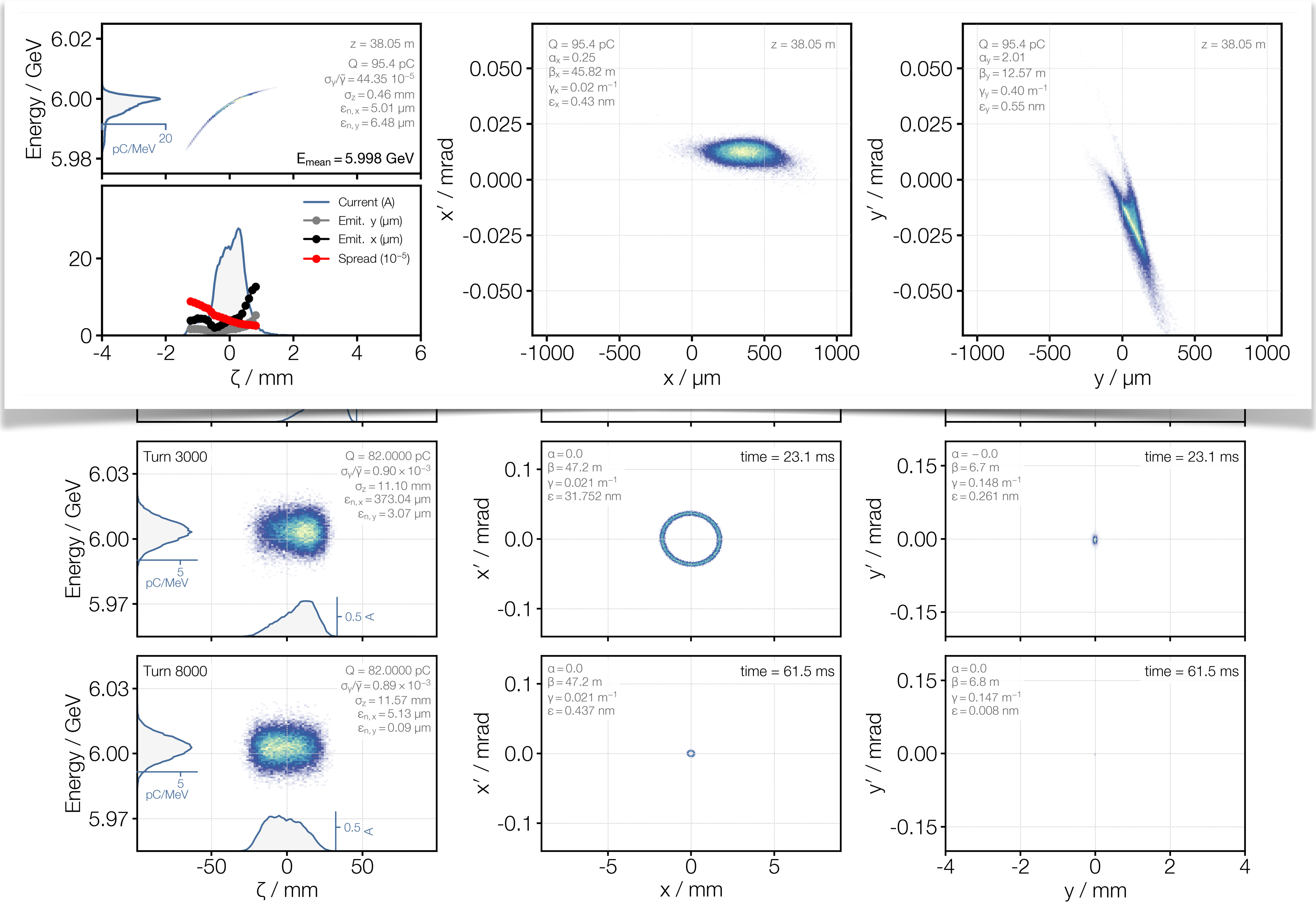
PETRA IV tracking — ELEGANT

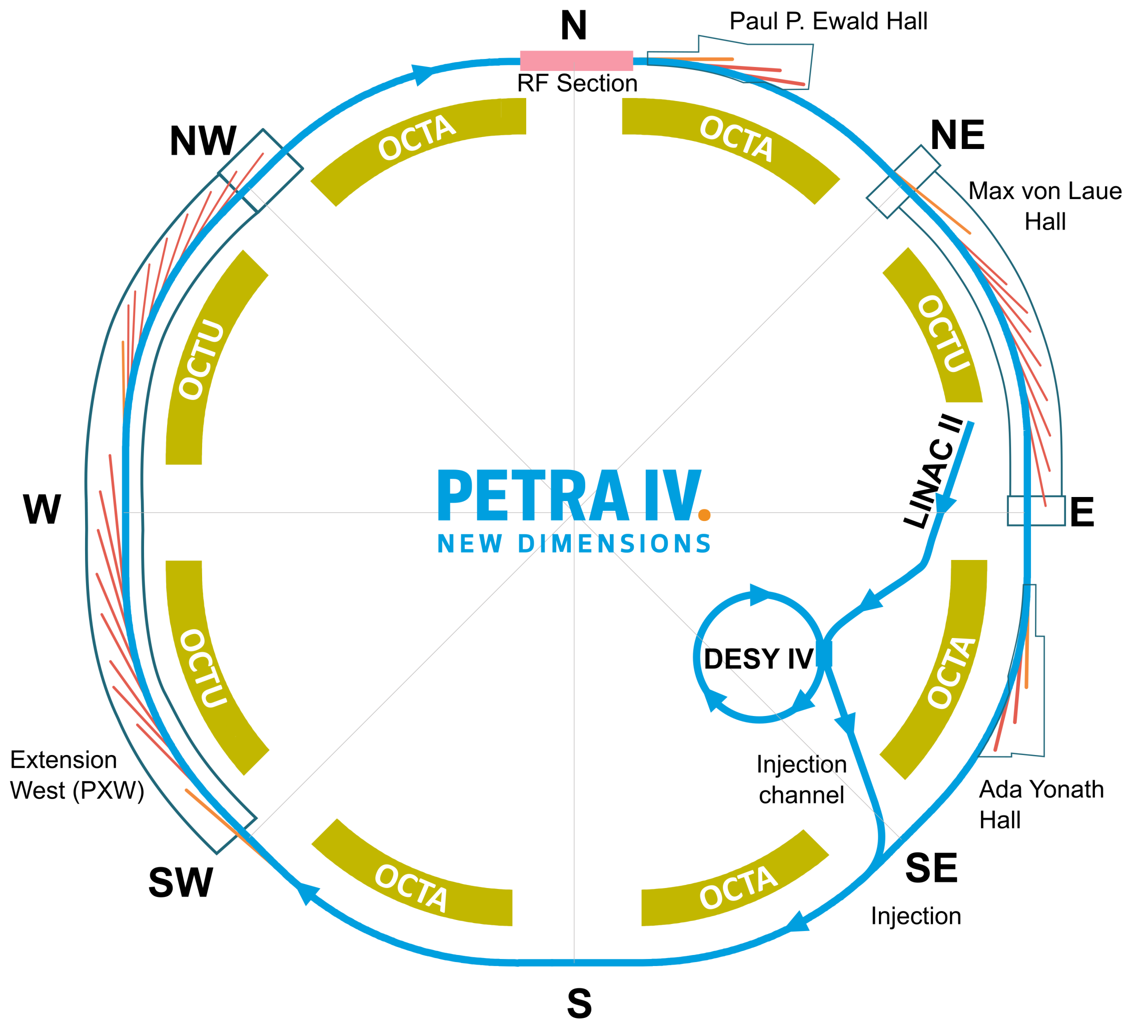
- Simulation for 8000 turns (3 x damping time)
- No particle losses.

The Plasma Injector: injection into PETRA IV

PETRA IV tracking with ELEGANT

All jitter sources at "two-sigma"





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The Plasma Injector: injection into PETRA IV

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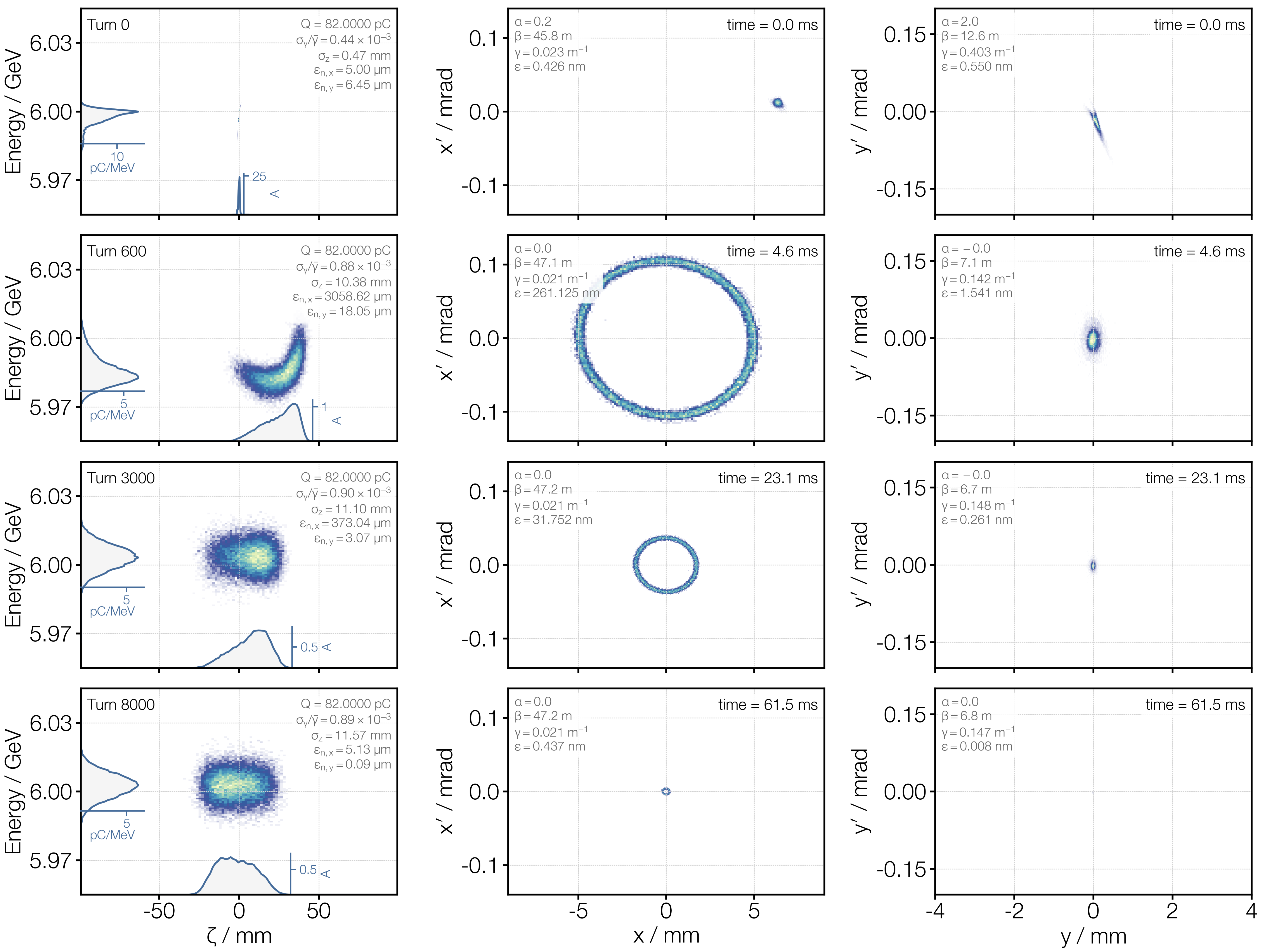
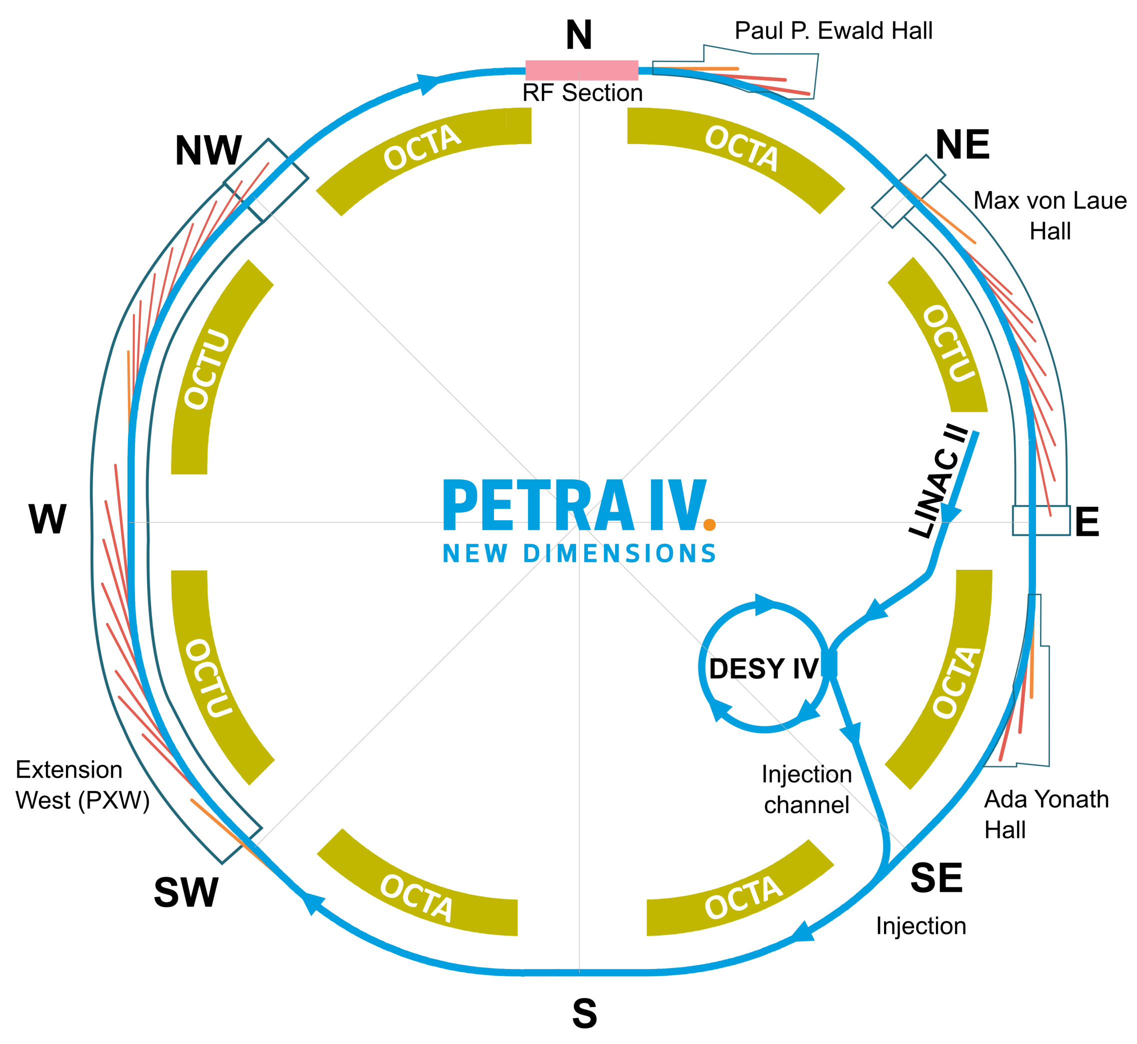




PETRA IV tracking — ELEGANT

- Simulation for 8000 turns (3 x damping time)
- No particle losses.

The Plasma Injector: operational requirements

Filling the ring from scratch requires high repetition rate

Operational requirements

For a plasma injector shot charge: ~80 pC.

Repetition rate		
Operation mode	Brightness	Timing
Initial filling	**> 32 Hz**	> 14 Hz
Top-up	> 0.5 Hz	> 0.4 Hz

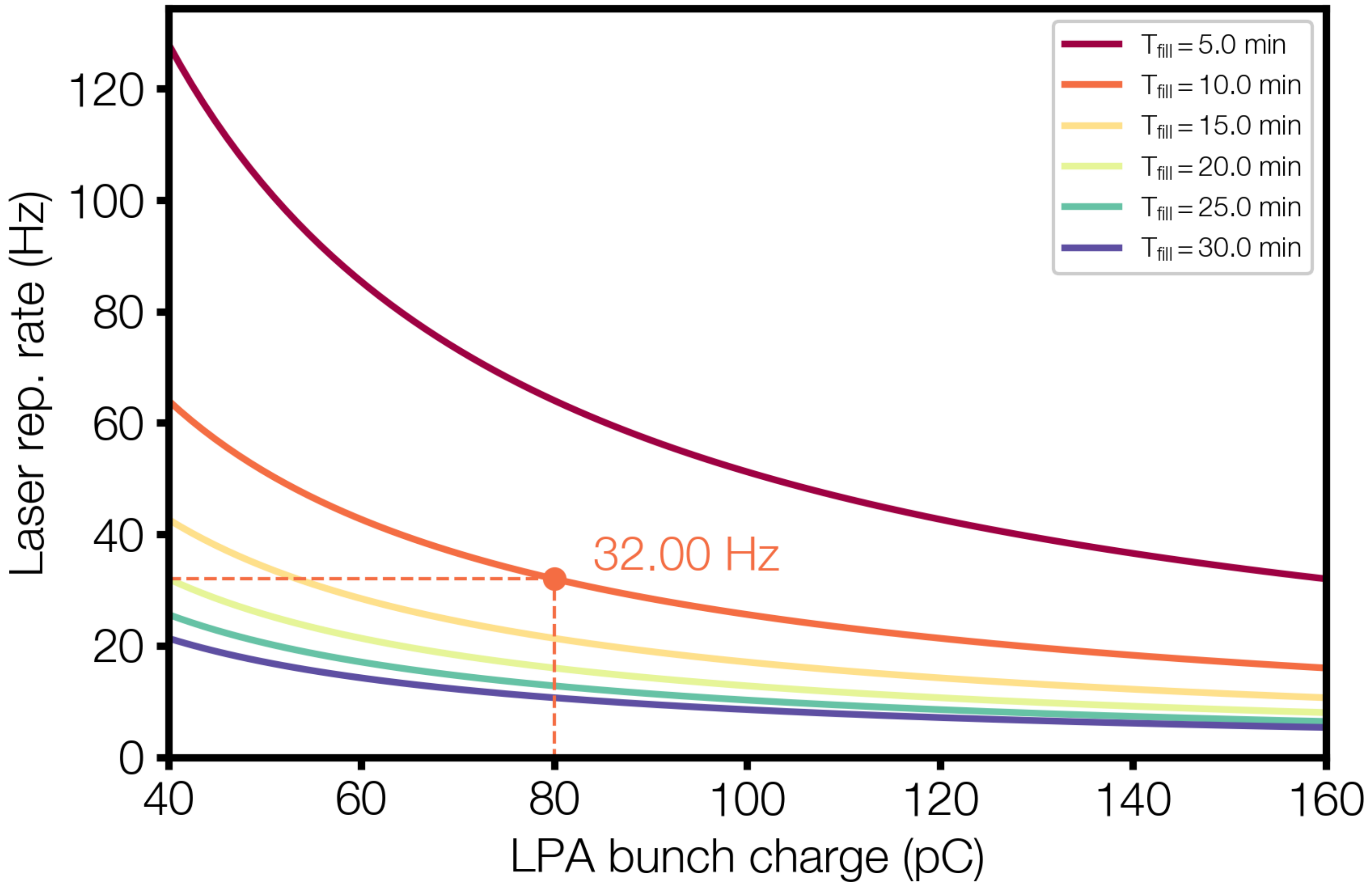


TABLE VI. Operational injection parameters of the plasma injector in Brightness and Timing modes.

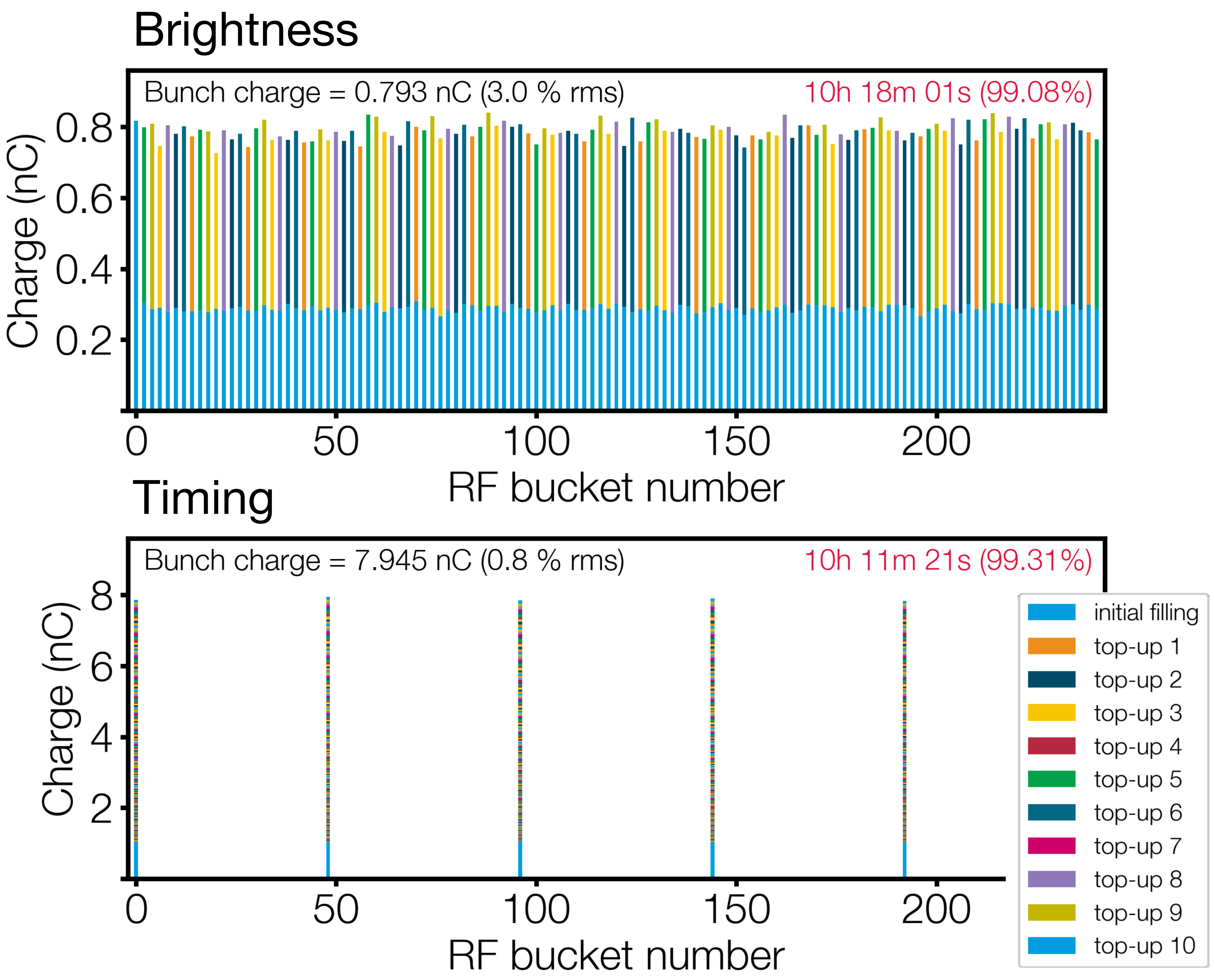
Beam mode	Brightness	Timing
Number of bunches	1920	80
Bunch charge / nC	0.8	8.0
Total charge / nC	1536	640
Initial filling		
Shot charge / pC	80	80
Injection frequency / Hz	32	32
Number of shots	19200	8000
Filling time / s	600	250
Top up		
Shot charge / pC	80	80
Top-up period / s	360	180
Number of shots	192	80
High rep.		
Injection frequency / Hz	32	32
Top-up time / s	6	2.5
Duty cycle	1/60	1/72
Low rep.		
Injection frequency / Hz	5	5
Top-up time / s	38	16
Duty cycle	1/10	1/10

The Plasma Injector: operational performance

Simulating operation for PETRA IV

Bunch charge variations

- Injector shot charge fluctuations (jitters) results in PETRA IV bunch charge variations.
- Ring operation “simulation”: filling and top up for different shot charge jitters: 0%, 5% and 10%
- Sizeable bunch variations in Brightness mode even for a non-fluctuating short charge.
- Performance of the plasma injector in terms of bunch charge fluctuation does not differ significantly w.r.t. conventional.



The Plasma Injector: operational performance

Simulating operation for PETRA IV

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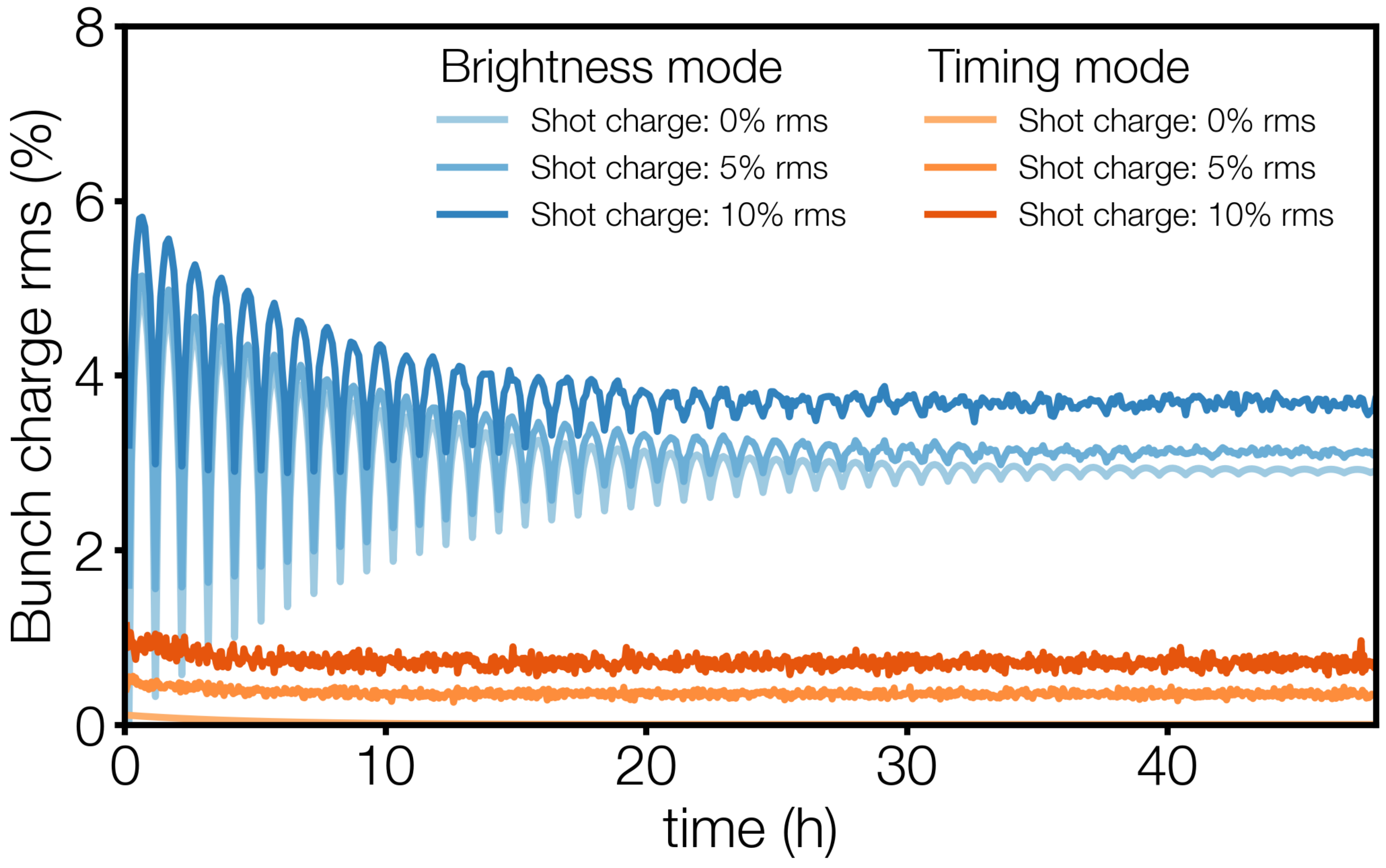

The Plasma Injector: power consumption

A substantial reduction of the energetic footprint is expected

LPA power consumption

- Maximum beam power (Brightness):
  6 GeV × 2.6 nC/s = 15.6 W
- The laser power is given by the efficiency:
  wall-plug-to-laser × laser-to-beam
- WP1: average laser-to-beam efficiency 2.6%.
  Optical power: 600 W
- Diode-pumped laser: Wall-plug efficiency 1%.
- Electrical laser power: 15.6 W / (0.026%) = 60 kW

Beamline power consumption

- Based on reported experience with LUX, FLASH and ARES.

LPA power consumption		
Laser type	**Flashlamp**	**Diode**
Operation	Top-up	**Full**
Wall-plug eff.	0.1%	**1 %**
Pulse energy	20 J	20 J
Rep. rate	5 Hz	30 Hz
Electric power	100 kW	**60 kW**
Cooling	60 kW	40 kW

Diode-pumped technology is key to deliver a competitive, energy-saving alternative.

The Plasma Injector: power consumption

A substantial reduction of the energetic footprint is expected

LPA power consumption

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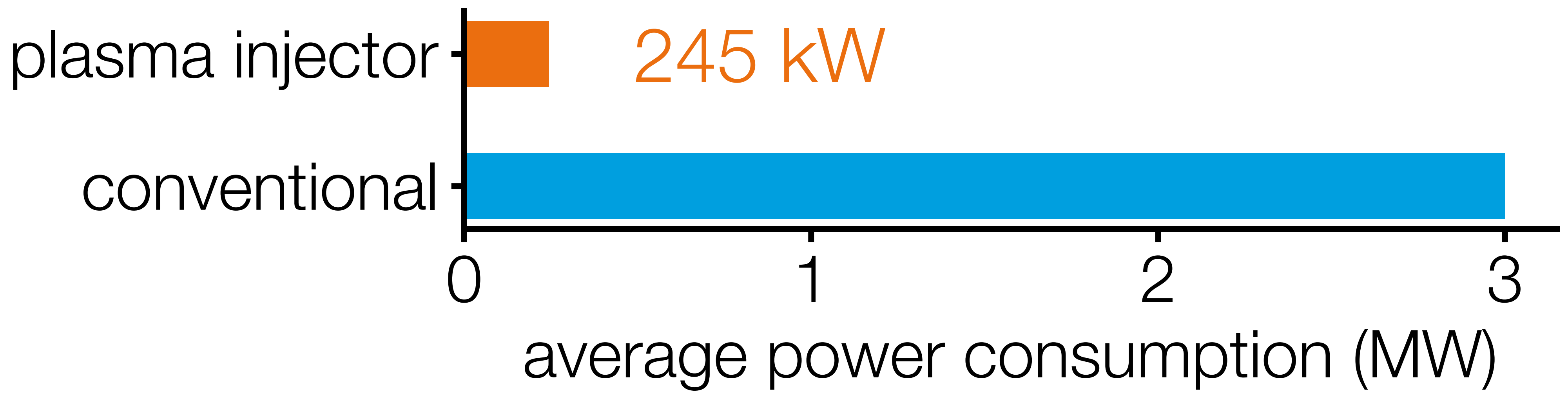
Beamline power consumption

- Based on reported experience with LUX, FLASH and ARES.

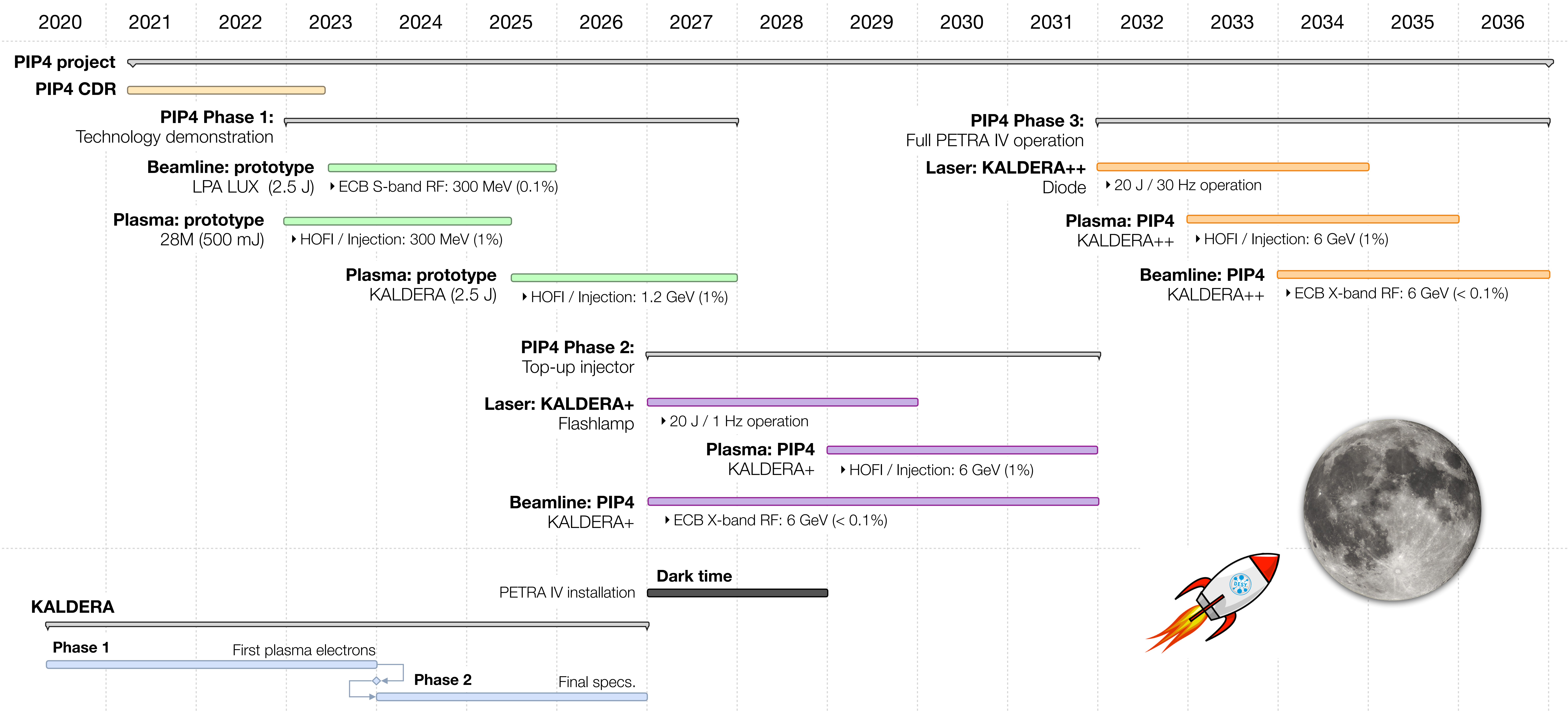
TABLE VII. Average power consumption of the plasma injector when filling the PETRA IV storage ring at 32 Hz with a diode-pumped laser system.

Laser system	60 kW
Laser cooling	40 kW
Magnets	60 kW
RF system	40 kW
Magnet & RF cooling	15 kW
Vacuum system	20 kW
Miscellaneous	10 kW
Total	**245 kW**



The Plasma Injector for PETRA IV

Technical Design Phase Roadmap



The Plasma Injector for PETRA IV: CDR

Summary and outlook

- Conceptual design
  - State-of-the-art LPA: 6 GeV — 1% spread and deviations, all jitters included.
  - Novel ECB with X-band RF: 6 GeV — 0.04%, maximizing charge stability and throughput.
  - Compact solution: < 50 m.
- Performance demonstrated through full S2E simulations
  - Operation with 80 pC (10% rms) does not differ significantly w.r.t. conventional.
  - Energy consumption at 32 Hz with diode-pumped Ti:Sa laser: 245 kW.
  - Factor 10 reduction w.r.t the conventional system for PETRA IV.
- Outlook
  - Phase 1: R&D phase: laser, plasma and beamline development.
  - Phase 2: Top-up operation at <5 Hz with flashlamp-pumped KALDERA+ upgrade.
  - Phase 3: Full PETRA IV operation at ~30 Hz with a diode-pumped KALDERA++ upgrade.