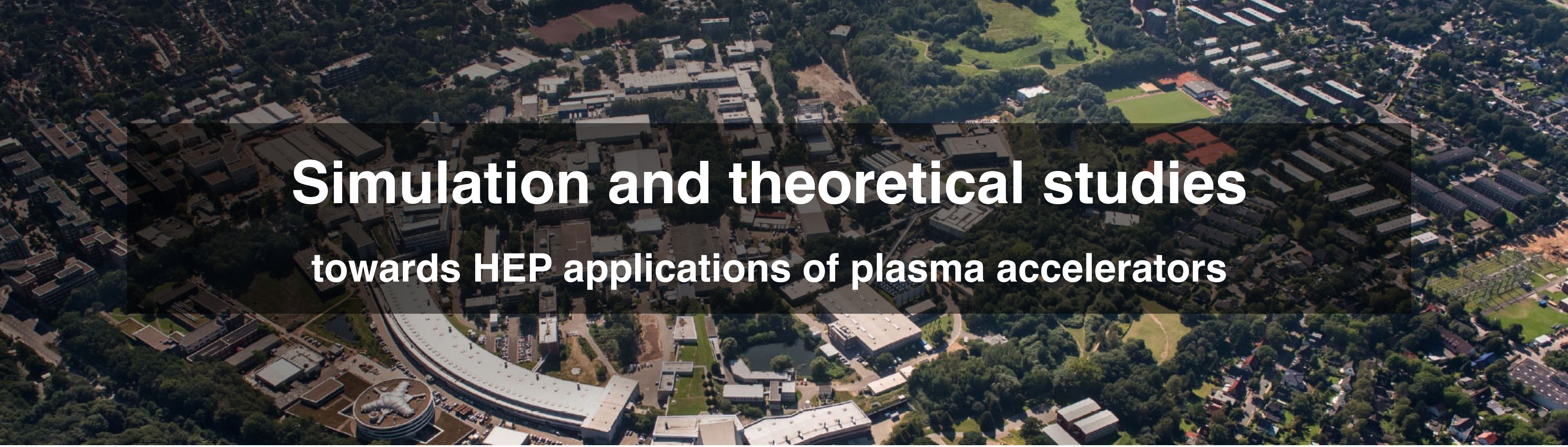


# Simulation and theoretical studies

## towards HEP applications of plasma accelerators

Maxence Thévenet – DESY

10.07.2024, LCWS24

The University of Tokyo, Japan

- ➢ A plasma injector for Petra IV
- ➢ Flat beams in plasma accelerators

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

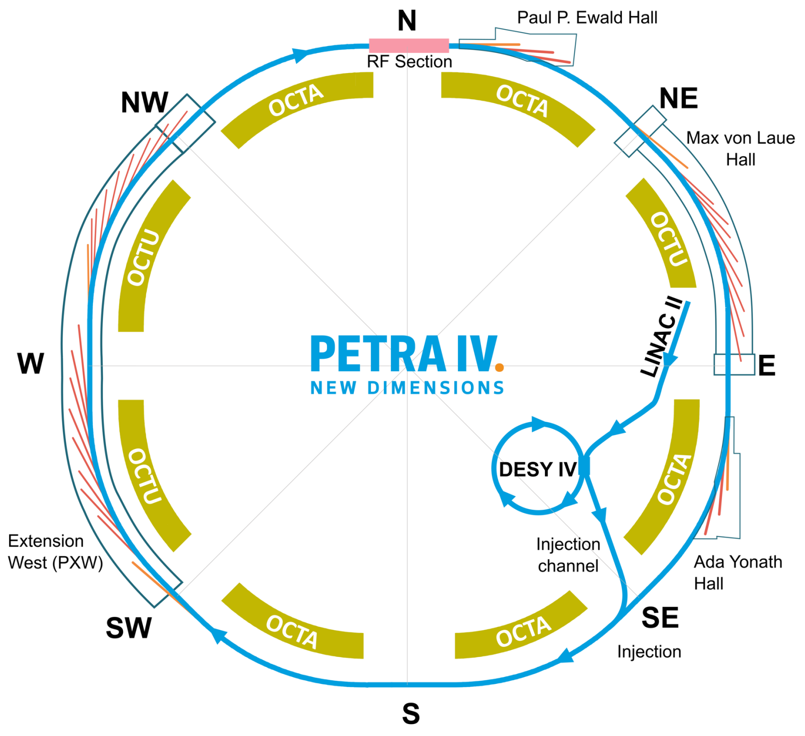
- A plasma injector for Petra IV
- Flat beams in plasma accelerators

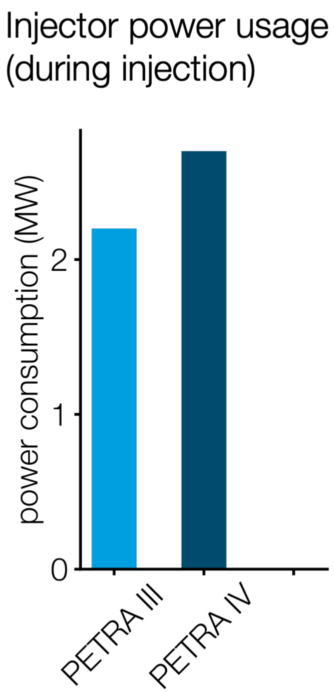
I. Agapov, S. Antipov, R. Brinkmann, A. Ferran Pousa, S. Jalas, L. Jeppe, M. Kirchen, W. P. Leemans, A. R. Maier, **A. Martinez de la Ossa**, J. Osterhoff, R. Shalloo, M. Thévenet, P. Winkler

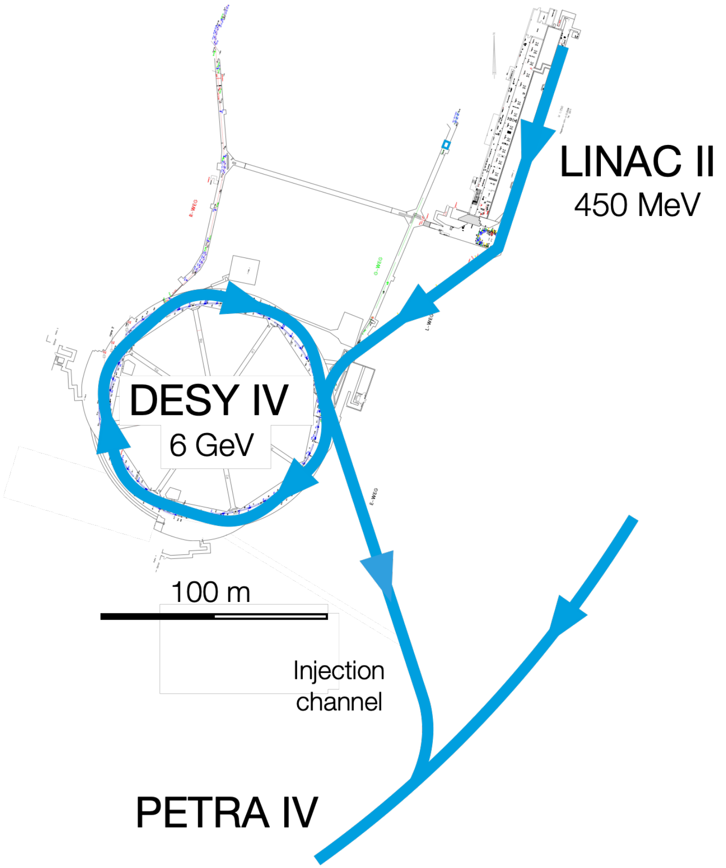
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

# Petra IV: record brightness for  6 GeV storage ring

*Petra IV [1] is the upgrade of the Petra III storage ring for synchrotron radiation (2.3 km, 6 GeV), proposing orders-of-magnitude increase in x-ray brightness.*







[1] https://www.desy.de/research/facilities__projects/petra_iv

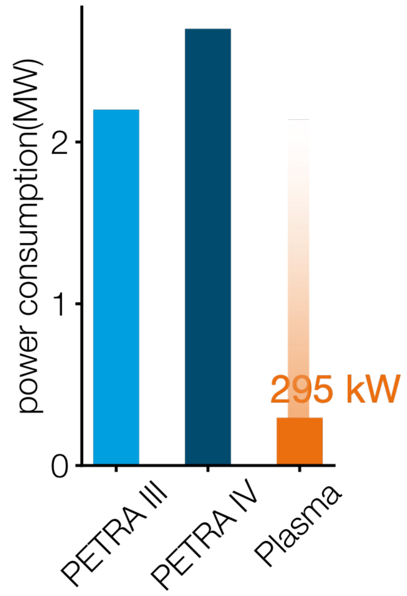
# A plasma-based solution could be compact and energy efficient

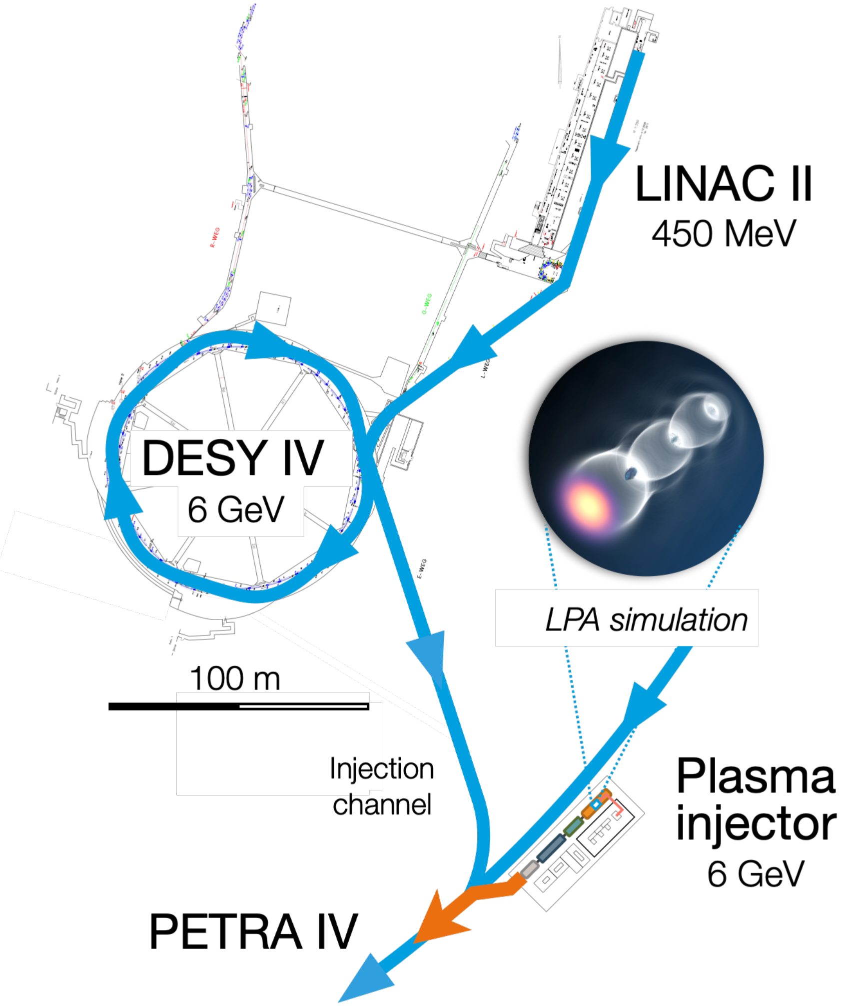
- **Compact –** Laser-plasma acc. + beamline:  < 50 m
- **Cost-effective –** Power consumption: < 500 kW
- **Competitive –** Full PETRA IV operation (fill + top-up)

**Key challenges**

- Energy gain **6 GeV**
- Energy spread and jitter: **< 0.3 %**
  *to maximize charge throughput and stability*
- Charge injection rate: **> 2.6 nC/s**
  *to fill the ring in < 10 minutes*
- Availability: **> 98%**
  *for users' satisfaction*

Injector power usage
(during injection)





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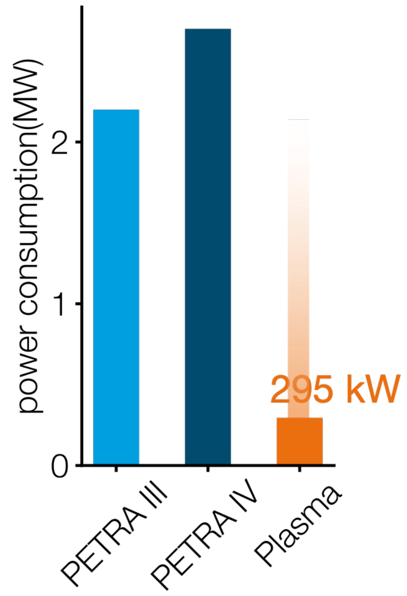
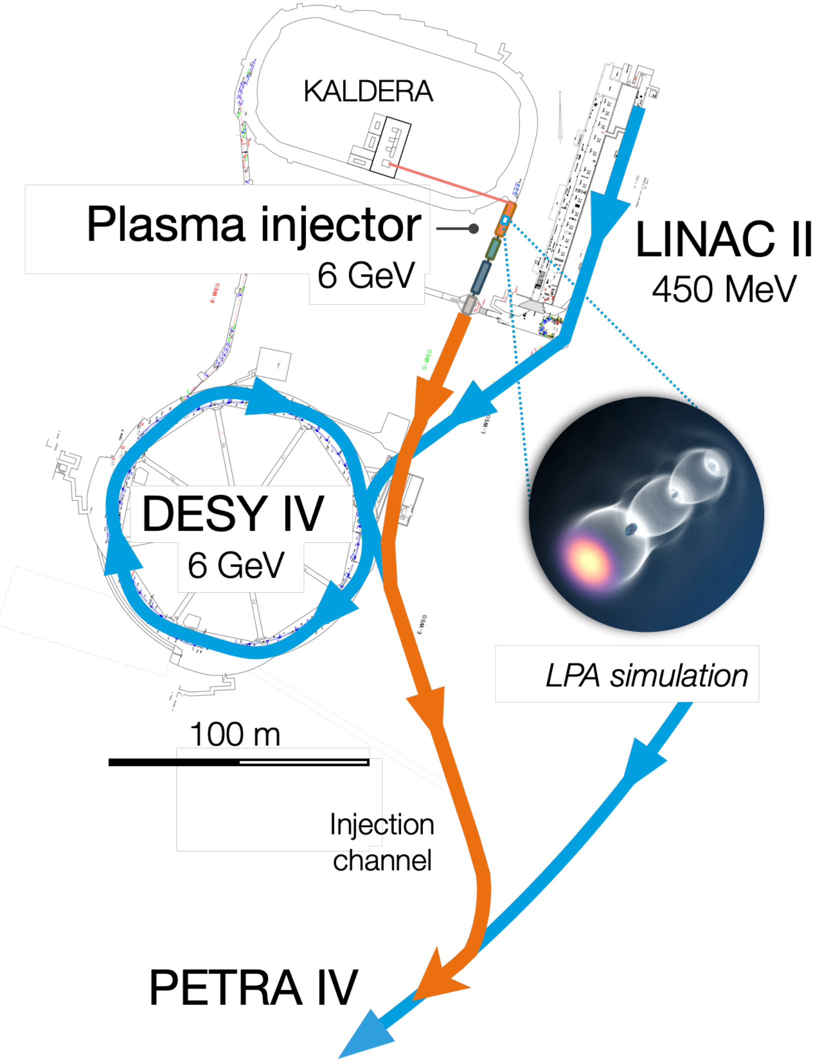
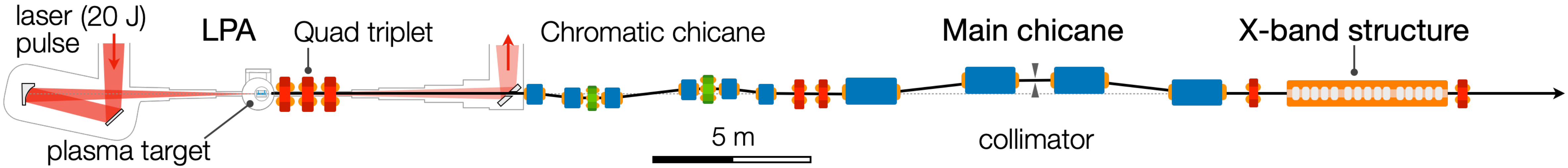


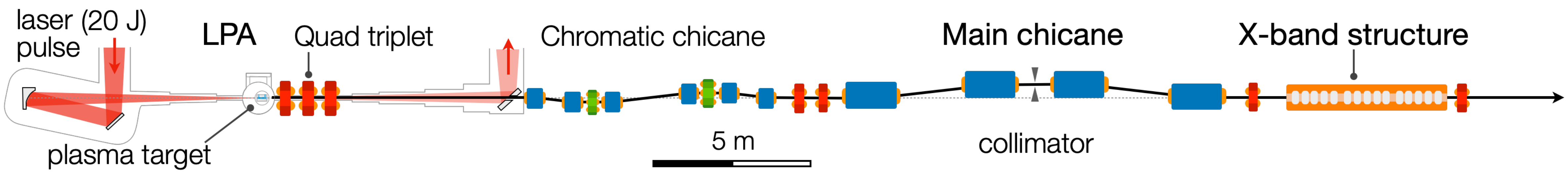


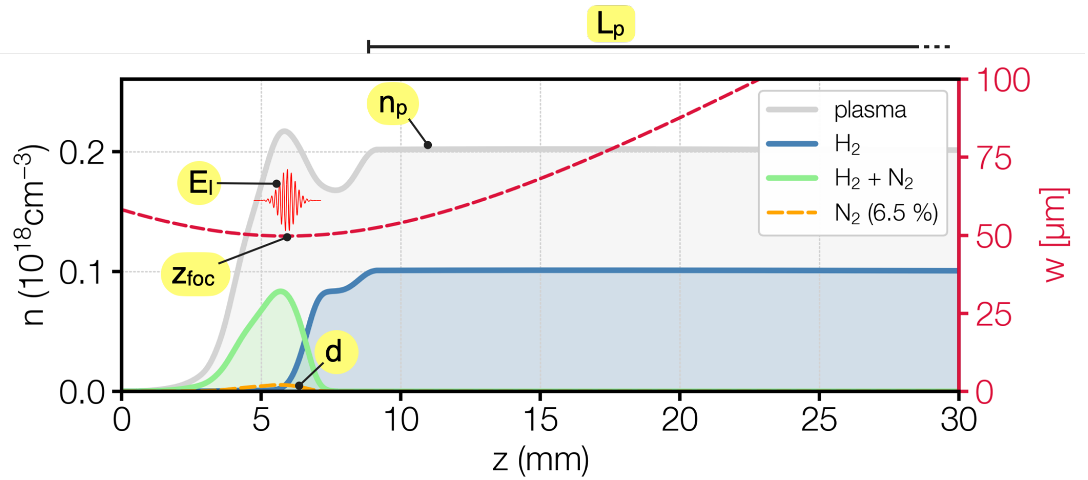
# The plasma injector design: reliable LPA + energy compression

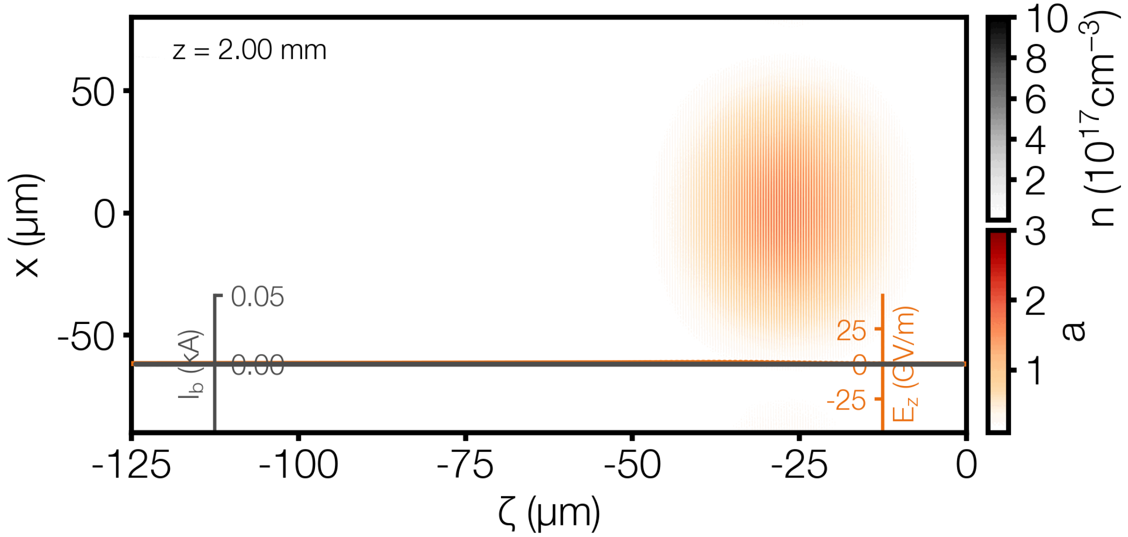


- ➢ Combines successful LPA development at DESY (LUX) and laser guiding.
- ➢ Energy compression beamline (ECB) to improve energy bandwidth and stability.
- ➢ State-of-the-art numerical tools and advanced optimization.

# The LPA: controlled injection and guiding in stable operation (LUX)



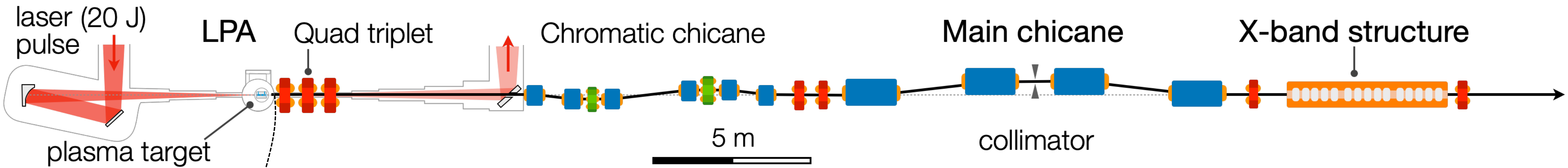


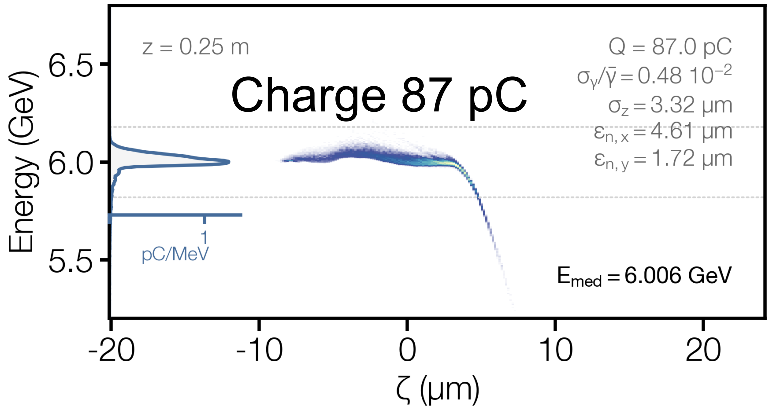


**Laser pulse:** Flattened Gaussian a0 = 2.0, w0 = 50 $\mu$m, 345 TW, 53 fs, 19.6 J.

**Plasma target:** LUX-type profile np = $2{\times}10^{17}\mathrm{cm}^{-3}$, 22 cm plateau. Transversely parabolic (HOFI) wm = 50 $\mu$m

# The ECB: controlling/correcting the beam’s energy spectrum



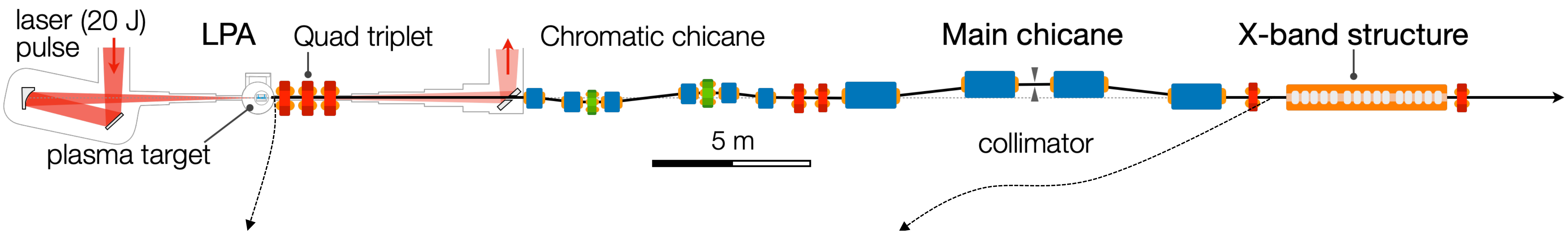


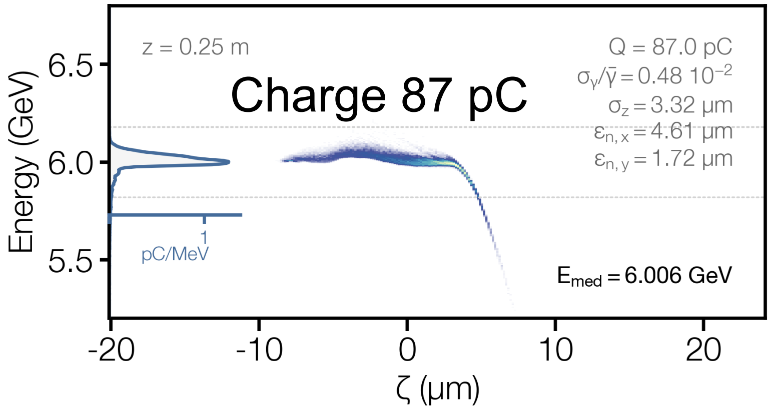
**After LPA**

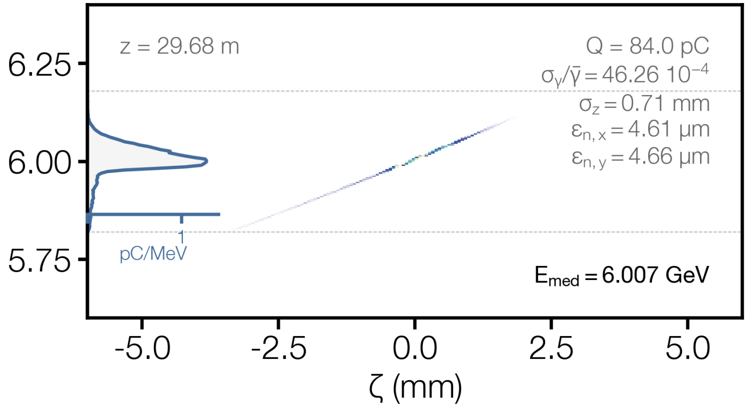
$\Delta\mathcal{E}/\mathcal{E} = 0.5\%\ \ \mathrm{L} = 3\ \mu\mathrm{m}$

Norm. emittance: 4.6 µm and 1.7 µm.
Divergence: 0.22 mrad and 0.12 mrad.
Efficiency: 2.7 %

# The ECB: controlling/correcting the beam’s energy spectrum







**After LPA**

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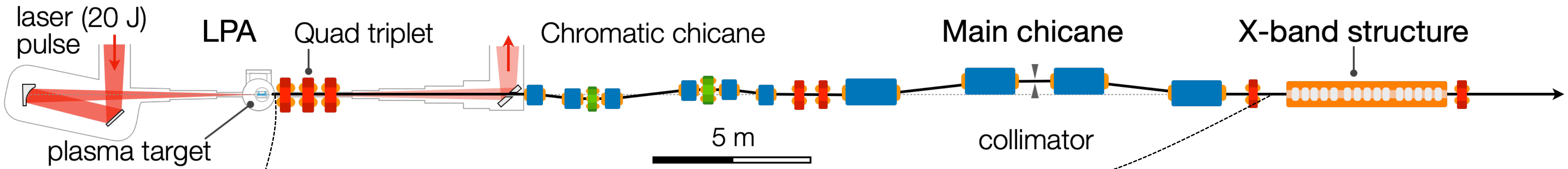
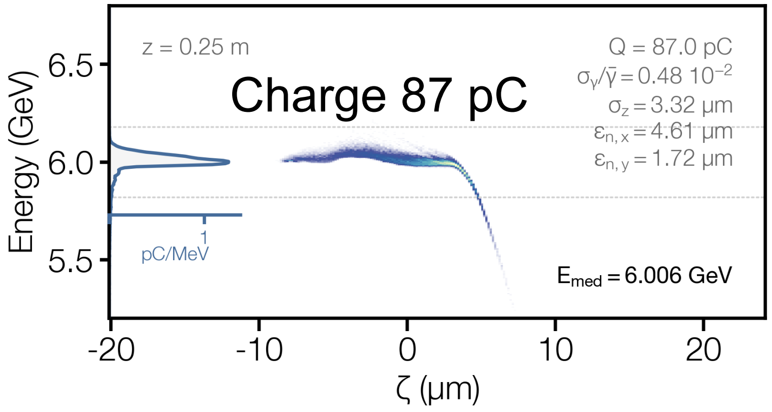
**After chicanes**

$\Delta\mathcal{E}/\mathcal{E} = 0.5\%$  L = 710 μm

# The ECB: controlling/correcting the beam’s energy spectrum





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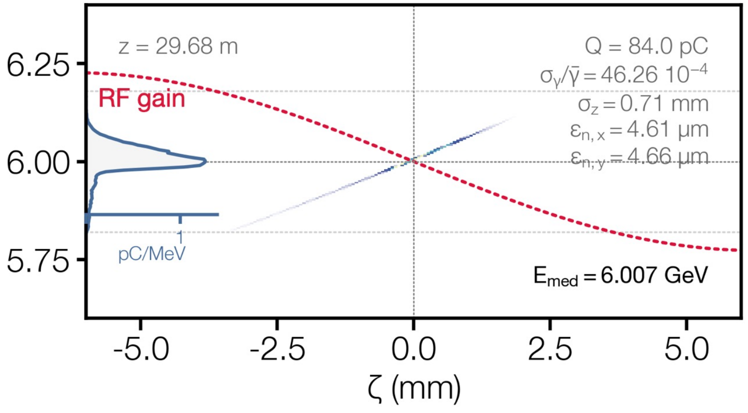
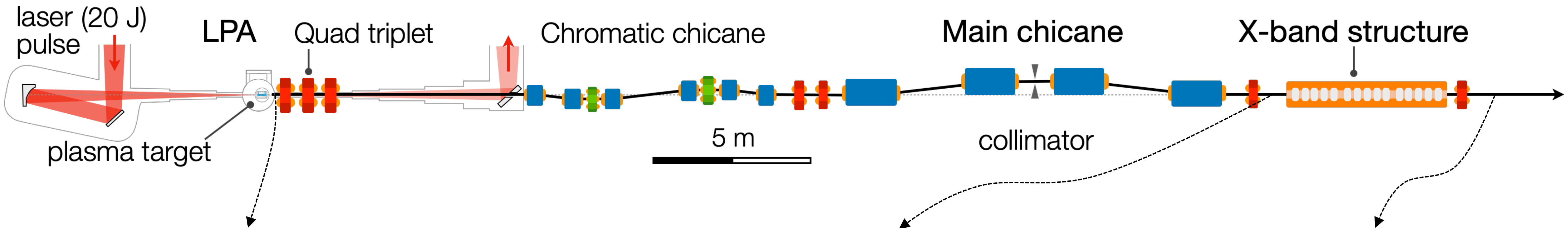
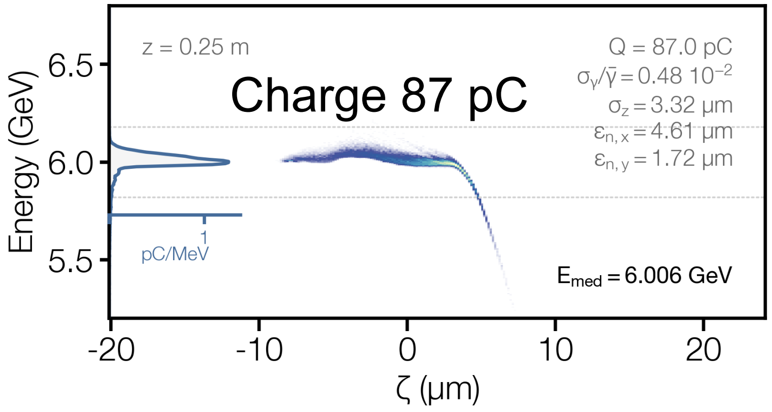


**After chicanes**

$\Delta\mathcal{E}/\mathcal{E} = 0.5\%\ \ \mathrm{L} = 710\ \mu\mathrm{m}$

# The ECB: controlling/correcting the beam’s energy spectrum





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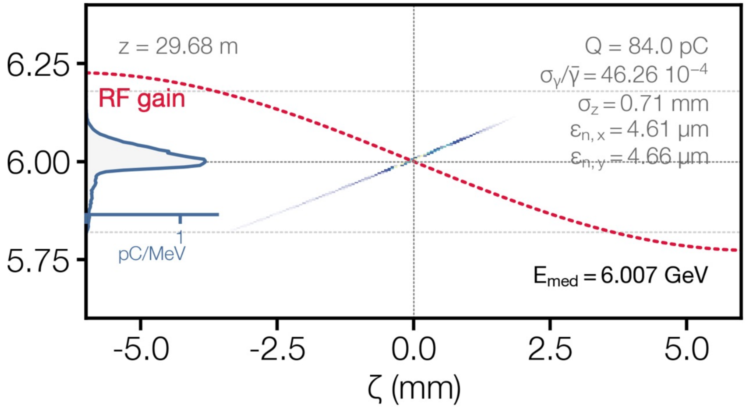

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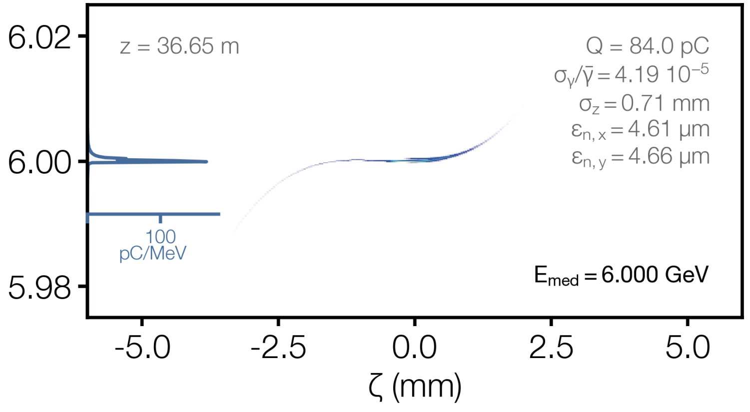
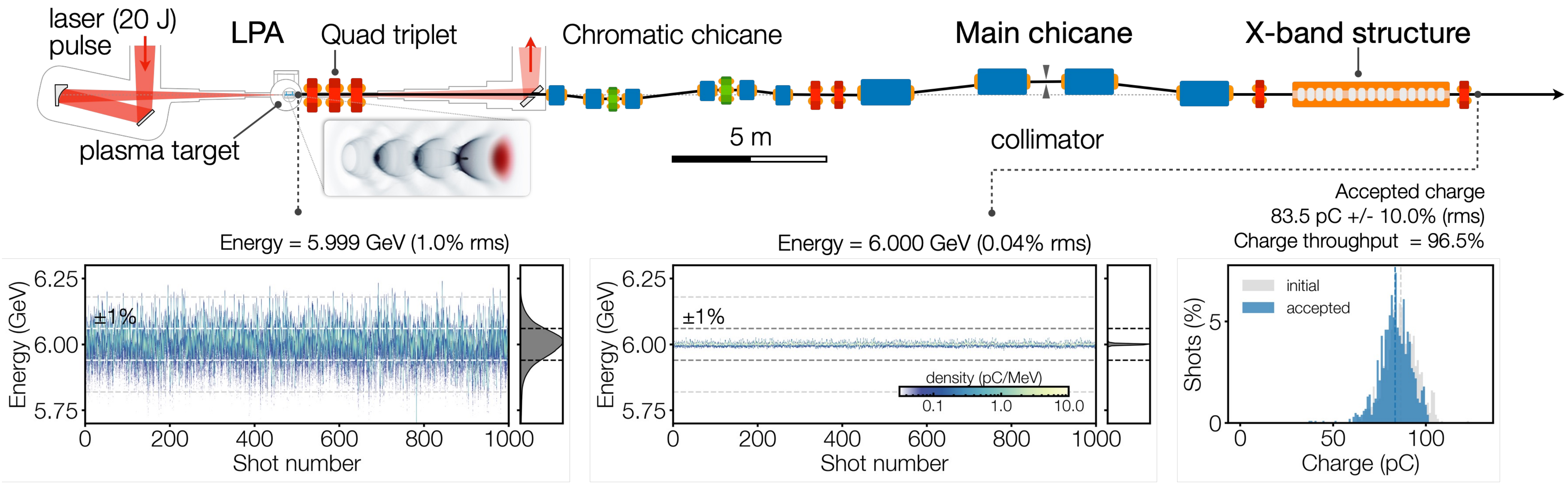


**After X-band structure**

$\frac{\Delta\mathcal{E}}{\mathcal{E}} < 0.1\ \%\ \mathrm{L} = 710\ \mu\mathrm{m}$

# Operational considerations and implementation plans



Energy = 5.999 GeV (1.0% rms)

Energy = 6.000 GeV (0.04% rms)

Accepted charge
83.5 pC +/- 10.0% (rms)
Charge throughput = 96.5%

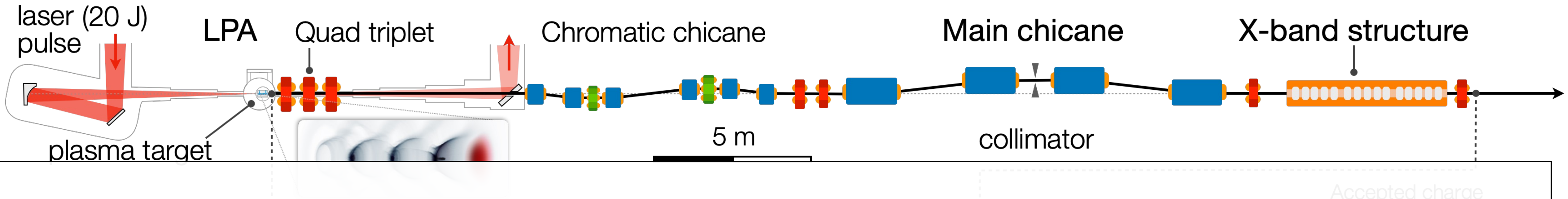
Jitters : {0.75 mm in $z_f$, 0.75% in $E_L$ , 0.75% in $n_p$, **0.2 mrad in $\theta_x$, 0.1 mrad in $\theta_y$, 100 fs in RF timing**}

*Introduced in FBPIC*

*Introduced in OCELOT*

Overall energy deviations reduced by factor 25 ➟ 0.04%
Charge throughput 96.5%

# Operational considerations and implementation plans



| 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 |

**Operation requirements and performance**

- Filling the ring in 10 min: 80 pC @ 32 Hz.
- Top-up 1% of charge: 6 s every 6 min.
- Power during filling: 300 kW.

Overall energy deviations reduced by factor 25 ➟ 0.04%
Charge throughput 96.5%

# DESY makes steps towards prototyping the plasma injector

Guido Palmer

**KALDERA laser**

Manuel Kirchen

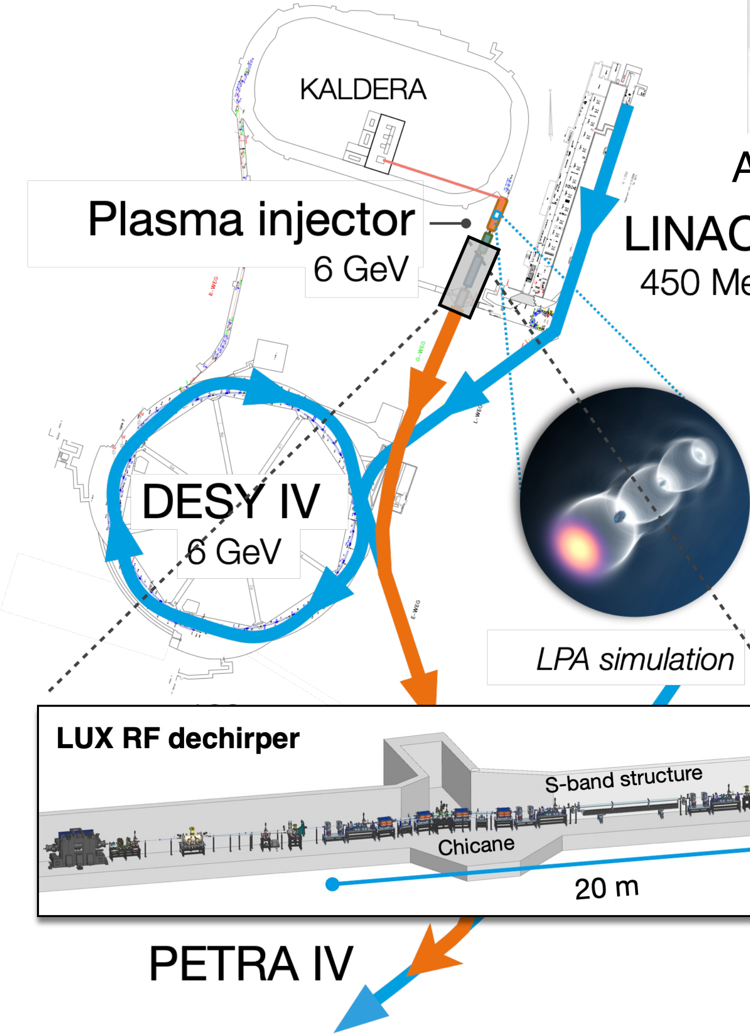
Rob Shalloo

**Plasma source**

*Emmy Noether Junior Research Group*

Paul Winkler

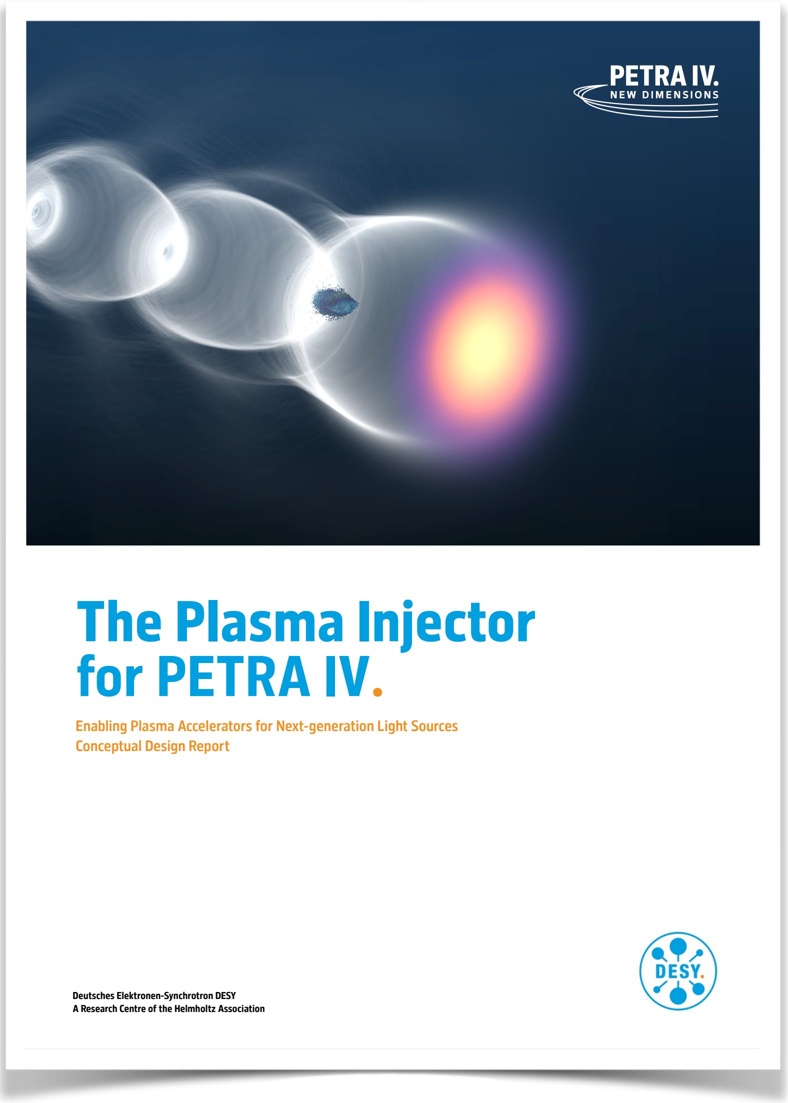
**Energy compression beamline**



Andreas R. Maier

*One goal is to demonstrate the full technology chain: laser, guiding, ECB, transport to inject into DESY II (500 MeV)*

# Conceptual Design Report to be published (58 p., internal review)



PETRA IV.
NEW DIMENSIONS

# The Plasma Injector for PETRA IV.

Enabling Plasma Accelerators for Next-generation Light Sources
Conceptual Design Report

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association

- A plasma injector for Petra IV
- Flat beams in plasma accelerators

**S. Diederichs**, C. Benedetti, A. Ferran Pousa, A. Sinn, J. Osterhoff, C. B. Schroeder, and M. Thévenet

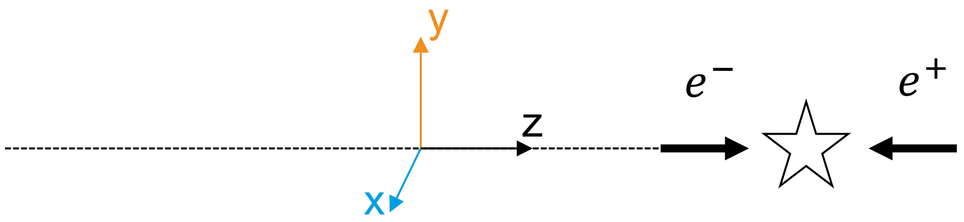
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

BERKELEY LAB

DESY.

# Flat beams are preferred at the interaction point



Beamstrahlung scales with[1] $\sim 1/(\sigma_x + \sigma_y)$

Luminosity scales with[2] $\sim 1/(\sigma_x \sigma_y)$ or $\sim 1/\sqrt{\epsilon_x \epsilon_y}$

→ Flat beams with $\sigma_x \gg \sigma_y$ $(\epsilon_x \gg \epsilon_y)$ minimize beamstrahlung and maximize luminosity

Acceleration of flat **beams not mentioned as a key R&D challenge** in ESPP


CERN-2022-001

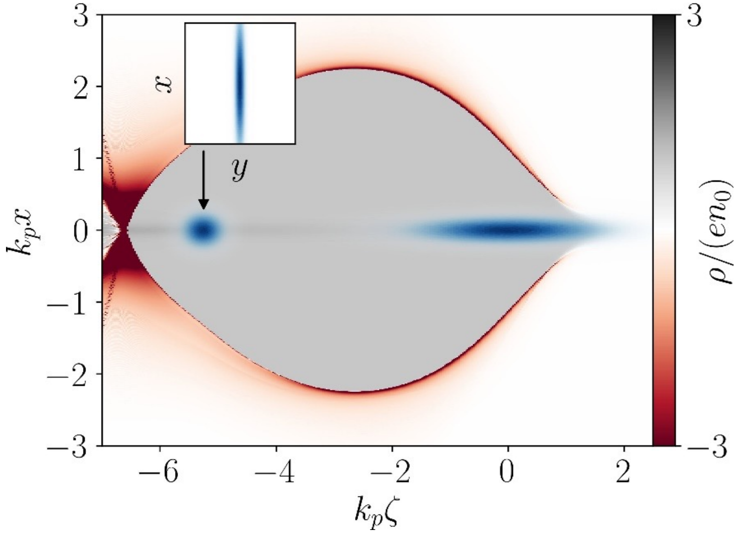
EUROPEAN STRATEGY FOR PARTICLE PHYSICS

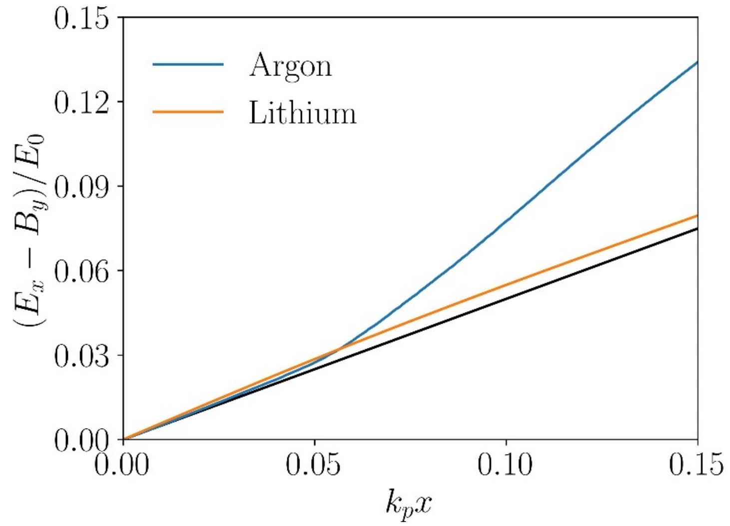
Accelerator R&D Roadmap

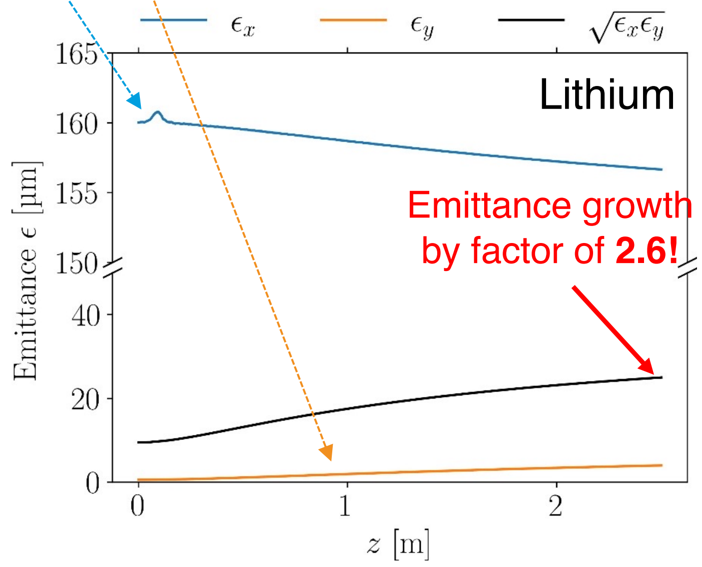
[1] Schroeder et al, JINST 2022
[2] Schulte, RAST 2016
[3] Raubenheimer, SLAC PUB 1993

# Realistic plasma stage sees considerable emittance exchange

- **Drive bunch**: Charge: 4.28 nC, Length (rms): 42 $\mu$m, $\epsilon_{[x,y]} = [60, 60]\,\mu$m.
- **Witness bunch**: Charge: 1.6 nC, Length (rms): 18 $\mu$m, $\boldsymbol{\epsilon_{[x,y]} = [160, 0.54]\,\mu}$**m.**
- **Plasma**: $n_0 = 7\times10^{15}$ cm$^{-3}$, Length: 2.5 m, Lithium.







Emittance growth by factor of **2.6!**

- Mild ion motion or ionization causes considerable emittance exchange

# Mechanism: coupled wakefields give coupled x & y orbits

*Consider the dynamics of a single beam electron in wakefield* $\boldsymbol{W} = \boldsymbol{E} + c\boldsymbol{e_z}\times\boldsymbol{B}$

**Ideal blowout regime**
**Axisymmetric and linear**

$$W_r = E_0 \frac{k_p r}{2}$$
$$W_x = E_0 \frac{k_p x}{2}$$
$$W_y = E_0 \frac{k_p y}{2}$$

$$r = \sqrt{x^2 + y^2}$$

→ *The x and y orbits are fully decoupled*

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→ *The x and y orbits are* *<u>fully decoupled</u>*

**Example**
**Axisymetric non-linear wakefields**

$$W_r = E_0\frac{k_p r}{2} + \alpha r^2$$
$$W_x = E_0\frac{k_p x}{2} + \alpha r x$$
$$W_y = E_0\frac{k_p y}{2} + \alpha r y$$

- Ion motion/ionization/... caused by an axisymmetric drive beam
- Guiding channel for LPA

→ *The x and y orbits are* *<u>coupled</u>*

# Mechanism: coupled wakefields give coupled x & y orbits

*Consider the dynamics of a single beam electron in wakefield* $\boldsymbol{W} = \boldsymbol{E} + c\boldsymbol{e}_z \times \boldsymbol{B}$

### Ideal blowout regime
### Axisymmetric and linear

$$W_r = E_0 \frac{k_p r}{2}$$
$$W_x = E_0 \frac{k_p x}{2}$$
$$W_y = E_0 \frac{k_p y}{2}$$

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### Example
### Axisymmetric non-linear wakefields

$$W_r = E_0 \frac{k_p r}{2} + \alpha r^2$$
$$W_x = E_0 \frac{k_p x}{2} + \alpha r x$$
$$W_y = E_0 \frac{k_p y}{2} + \alpha r y$$

- Ion motion/ionization/... caused by an axisymmetric drive beam
- Guiding channel for LPA

→ *The x and y orbits are coupled*

### General
### non-axisymmetric, non-linear fields

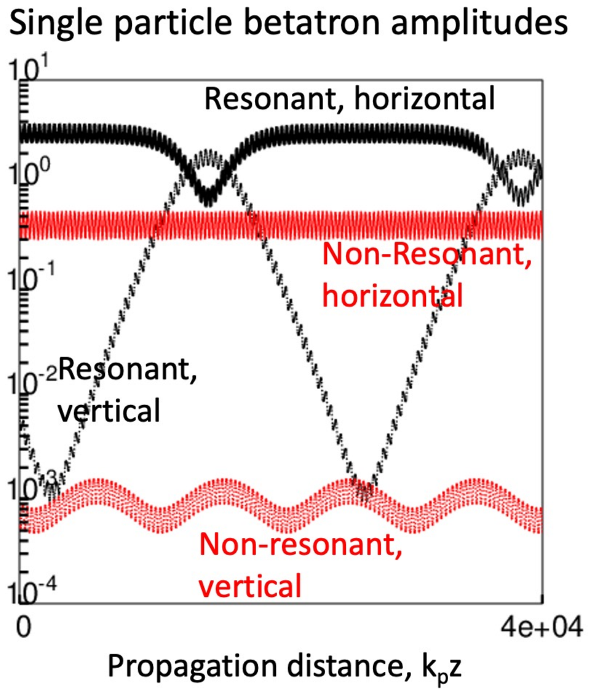
$$W_x = f(x, y)$$
$$W_y = g(x, y)$$

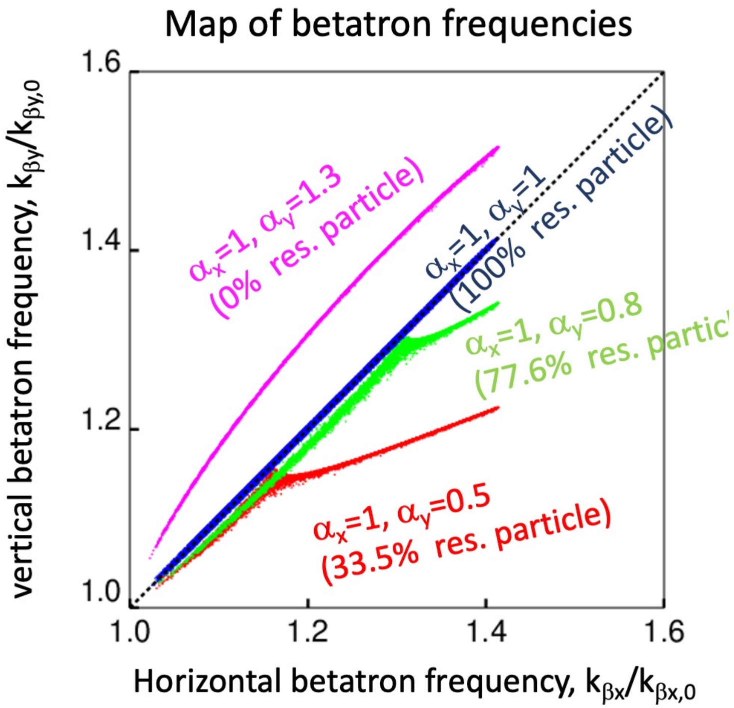
- Ion motion/ionization/… caused by a flat witness beam
- Laser misalignment in guiding channel for LPA

→ *The x and y orbits are coupled*

# A fraction of beam particles are trapped in a resonance

- Each electron has a different $k_{\beta x}$ and $k_{\beta y}$ depending on initial conditions.
- The resonance is located on the diagonal $k_{\beta x} = k_{\beta y}$.
- Electrons in a specific area are trapped in the resonance.
- These resonant electrons see periodic exchange in x and y orbits.
- They are responsible for the emittance exchange.





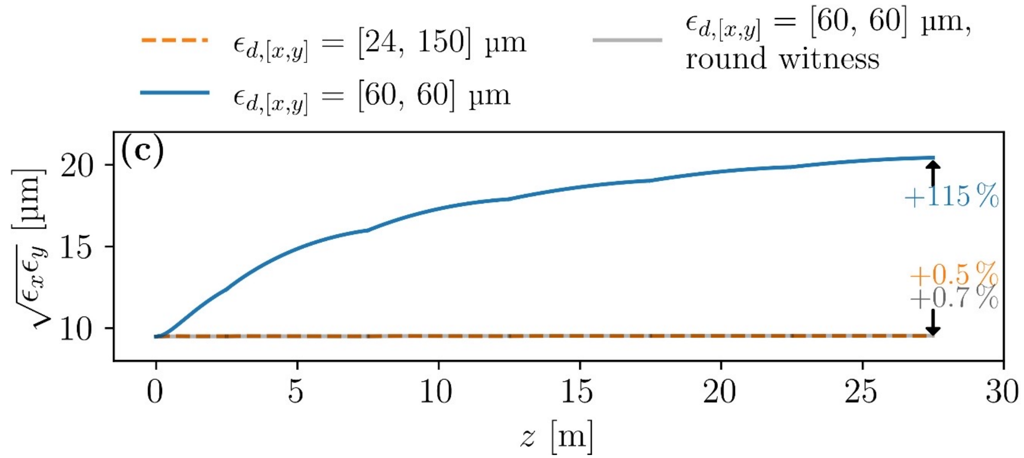
- ➢ Well-known (complex) phenomenon in RF accelerators
- ➢ Axisymmetric + non-linear is the worst case
  all particles are resonant → **full emittance exchange**

# No clear solution yet for a dense flat witness beam causing ion motion

**Ion motion caused by the driver only (6 HALHF stages)**

Driver: 4.28 nC, 42 $\mu$m, $\epsilon_{[x,y]} = [60, 60]\ \mu m$,$[24, 150]\ \mu m$
Witness: 1.6 nC, 18 $\mu$m, $\epsilon_{[x,y]} = [160, 0.54]\ \mu m$
Plasma: Sodium 1+, $n_0 = 7\times10^{15}\ cm^{-3}$, 2.5 + 5*5 m.

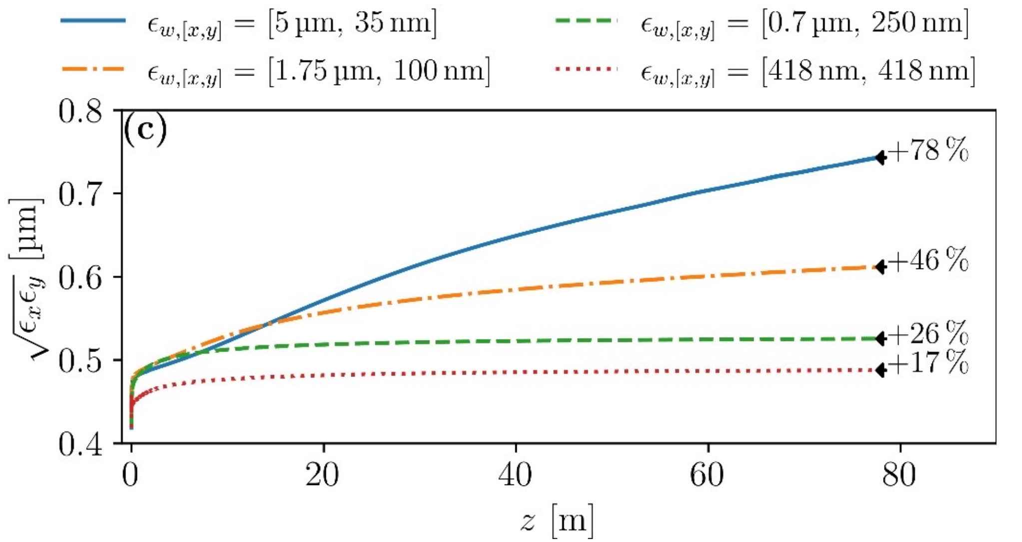
→ *A flat driver breaks the resonance and mitigates emittance exchange*



**Ion motion caused by the witness beam only**

Driver: 4.28 nC, 42 $\mu$m, $\epsilon_{[x,y]} = [2.8, 2.8]$ mm, rigid
Witness: 1.6 nC, 18 $\mu$m, $\epsilon_{[x,y]} = [5, 0.035]\ \mu m$
Plasma: Hydrogen, $n_0 = 7\times10^{15}\ cm^{-3}$, length 77.5 m

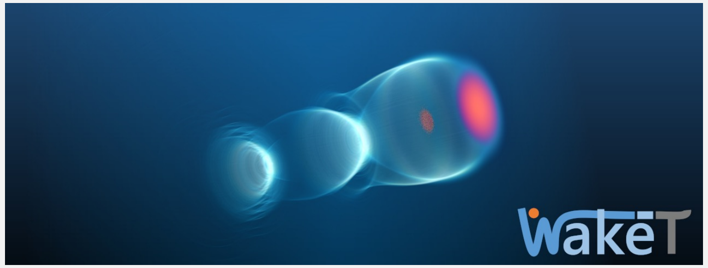
→ *A flatter beam causes larger emittance exchange*



# Studies made possible thanks to recent progress in simulations

## ➢ Wake-T

*Quick simulations (benchmarked vs. FBPIC)*

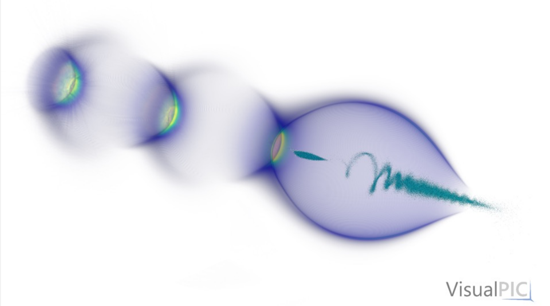


- ➢ 2D (axisymmetric) quasistatic
- ➢ Laser-driven or beam-driven
- ➢ Python, second/minutes on a laptop
- ➢ Recent: Adaptive grid & ion motion

Open-source https://github.com/AngelFP/Wake-T

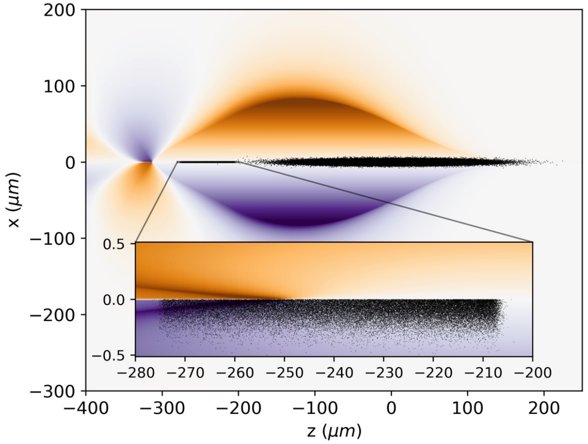
## ➢ HiPACE++

*Optimized for large 3D simulations*



- ➢ 3D quasistatic particle-in-cell
- ➢ Multi-physics
- ➢ C++, on top supercomputers
- ➢ Recent: Mesh refinement

Open-source https://github.com/Hi-PACE/hipace



DESY. BERKELEY LAB And others

- ➢ With mesh refinement, 3D simulations of a 20 GeV stage from 175 GeV, emittance 135 nm, are very affordable
  Numerical convergence with transverse resolution of **5 nanometers** to fully resolve ion motion effects

- ➢ Multi-stage simulation studies done routinely
  A. Ferran Pousa et al. Proc. IPAC'23 14: 1533-1536. ; S. Diederichs et al. arXiv:2403.05871 (2024).

- ➢ A collection of tools enables start-to-end multi-physics studies
  COMSOL-plasma for hydrodynamics simulations of HOFI, Optimas for scalable Bayesian optimization, LASY for laser manipulations

# Conclusion

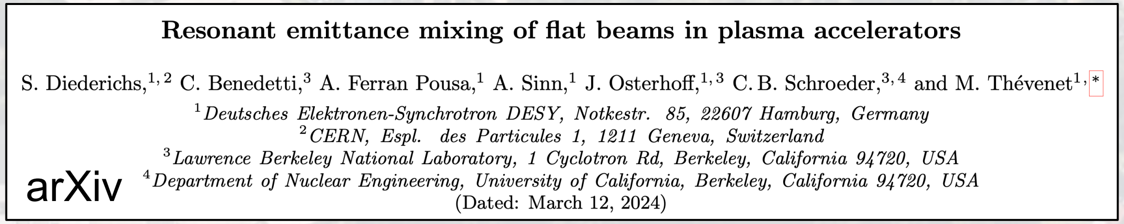
- **We propose a plasma injector for Petra IV.**
  - *6 GeV, < 0.3% energy deviation, 2.6 nC/s*
  - *Reliable 6 GeV LPA + energy compression beamline for energy spread & jitter reduction*
  - *CDR to be published soon*
- **Accelerating a flat beam in a plasma accelerator poses significant challenges.**
  - *Emittance is transferred from the large to the small direction, degrading quality*
  - *This is caused by particles falling in a resonance*
  - *Avoiding the resonance might mitigate this effect*
- **Full-physics realistic simulations are *very* affordable.**
  - *Progress in numerical methods makes most scenarios doable and cheap, even in 3D*


PETRA IV. NEW DIMENSIONS

The Plasma Injector for PETRA IV.

Enabling Plasma Accelerators for Next-generation Light Sources
Conceptual Design Report

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association


**Resonant emittance mixing of flat beams in plasma accelerators**

S. Diederichs,[1, 2] C. Benedetti,[3] A. Ferran Pousa,[1] A. Sinn,[1] J. Osterhoff,[1, 3] C. B. Schroeder,[3, 4] and M. Thévenet[1, *]

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[2] *CERN, Espl. des Particules 1, 1211 Geneva, Switzerland*
[3] *Lawrence Berkeley National Laboratory, 1 Cyclotron Rd, Berkeley, California 94720, USA*
[4] *Department of Nuclear Engineering, University of California, Berkeley, California 94720, USA*
(Dated: March 12, 2024)

arXiv

Thank you for your attention

# Conceptual Design Report to be published (58 p., internal review)

**Conceptual design**

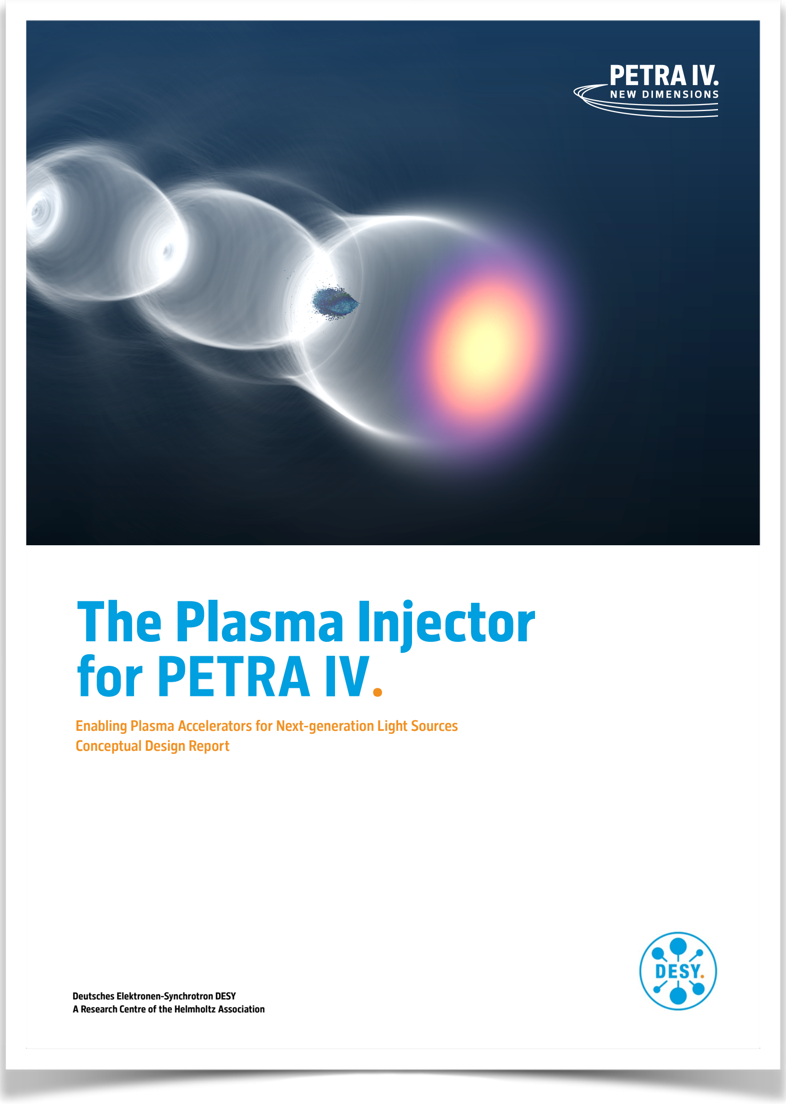
- State-of-the-art LPA: 6 GeV — <1% spread and deviations.
- Energy compression beamline with X-band RF: 6 GeV — 0.04%.
- Compact solution: < 50 m.

**Performance demonstrated through full S2E simulations**

- Operation with 80 pC (10% rms) similar to conventional.
- 32 Hz with diode-pumped Ti:Sa laser: 295 kW.

**Outlook**

- First prototyping under consideration at DESY.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