

PETRA IV.
NEW DIMENSIONS

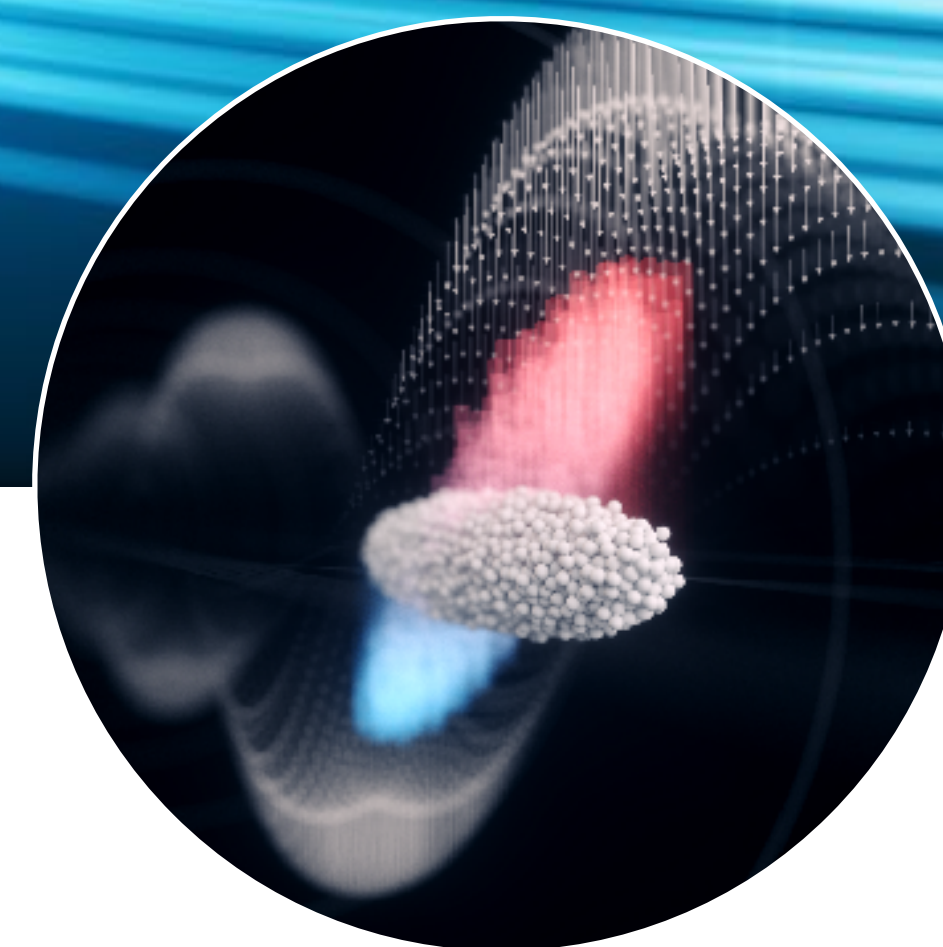
The 6 GeV plasma injector for PETRA IV

10th Low Emittance Ring Workshop

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Hamburg, October 10, 2025

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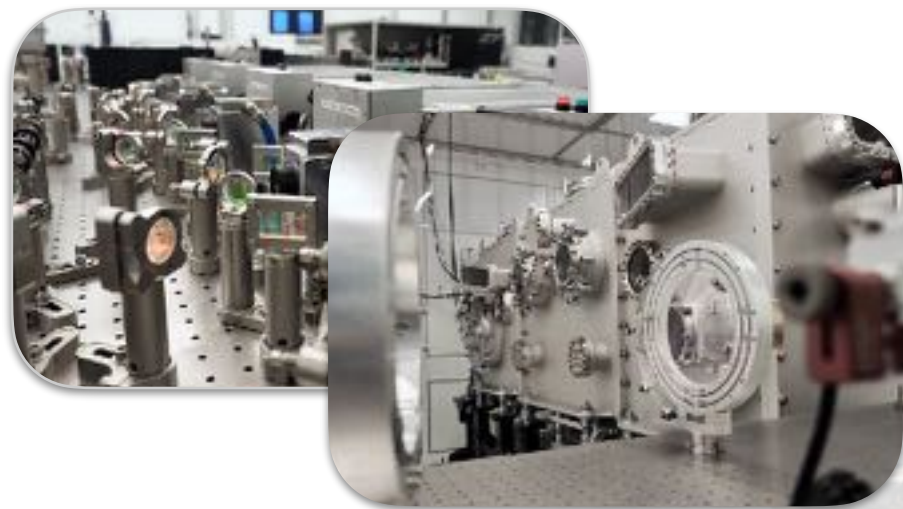
HELMHOLTZ



Plasma Accelerator R&D at DESY

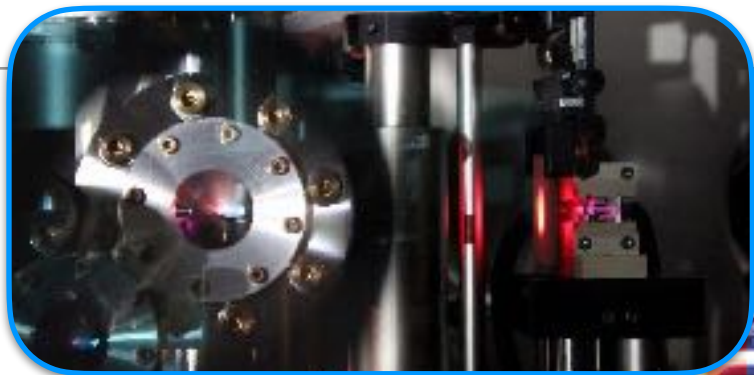
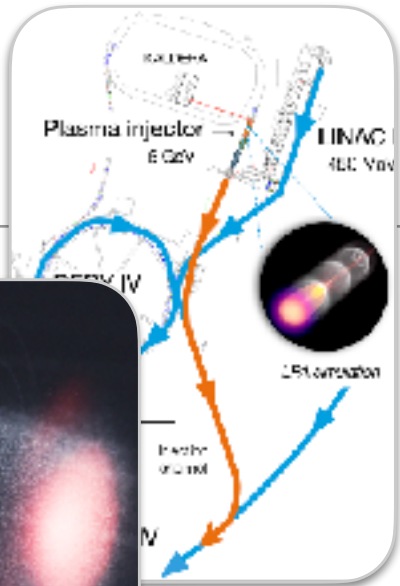
Our portfolio at plasma.desy.de

Scientific
Engineering



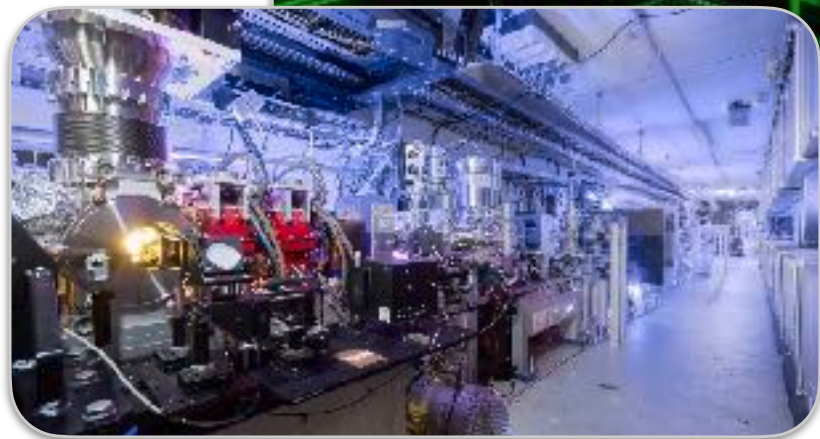
PETRA

Theory &
Simulations



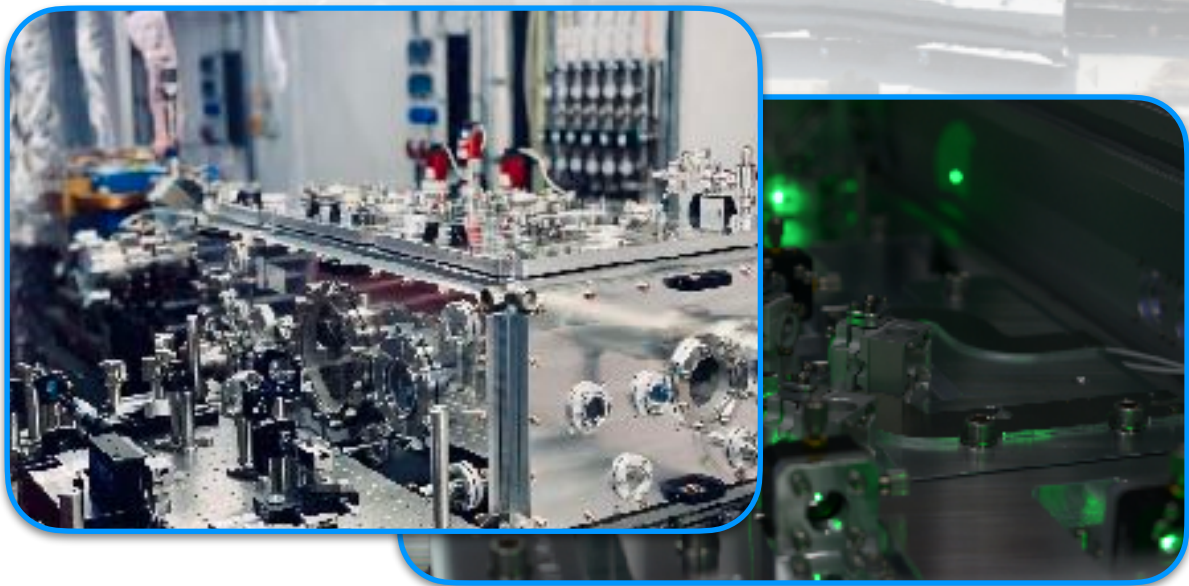
LPA Applications

- RF accelerators
- plasma accelerators

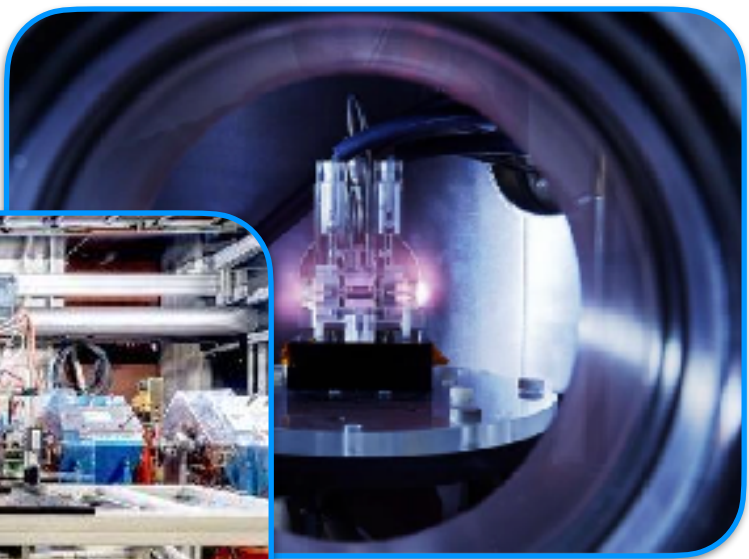


LUX Laser-Plasma
Accelerator

KALDERA
High Rep-Rate LPA



FLASHForward
Beam-Driven Plasma Acc.



Laser-Plasma Acceleration

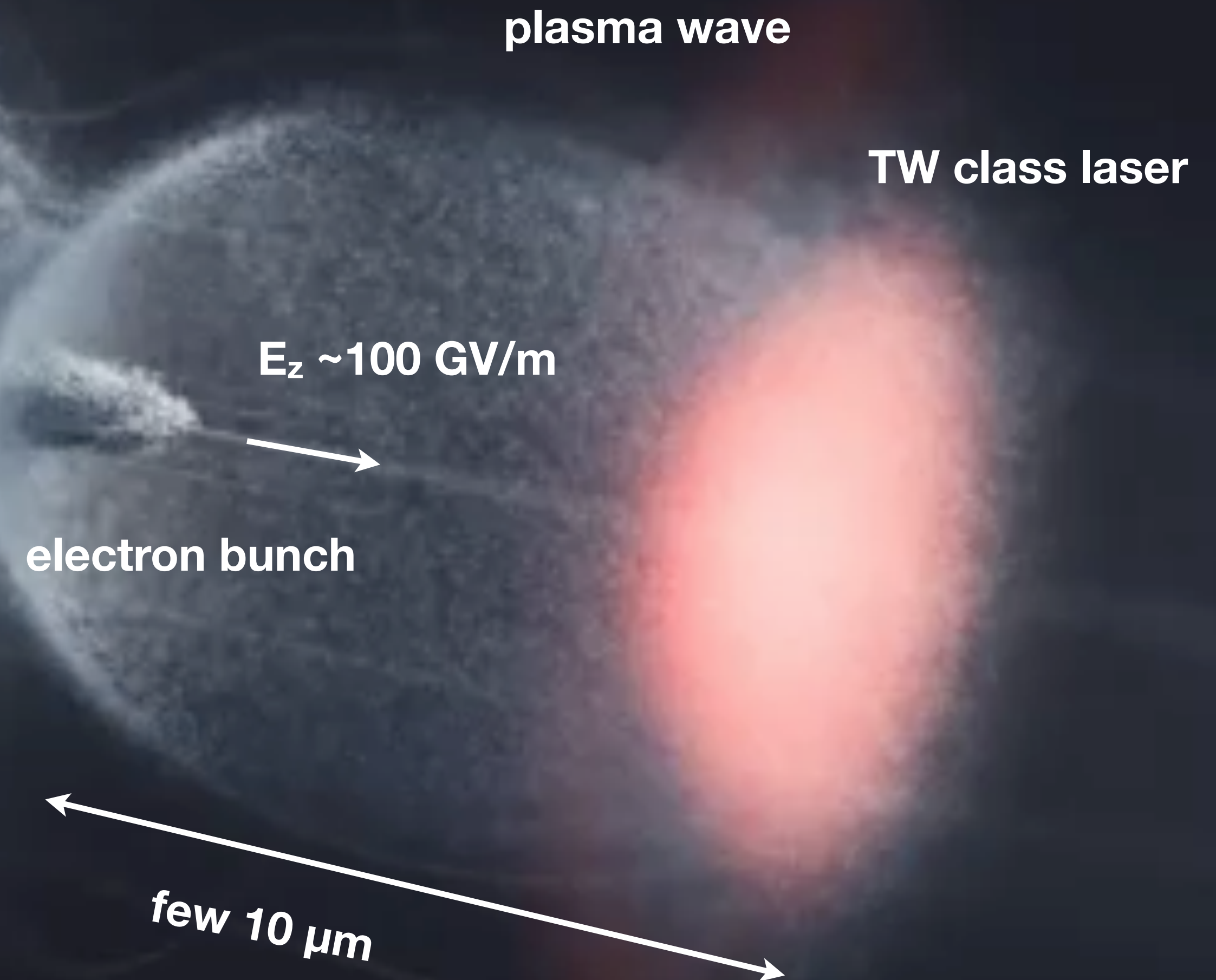
Orders of magnitude higher acceleration gradients

Promises

- > Compact foot print
- > Energy & cost savings

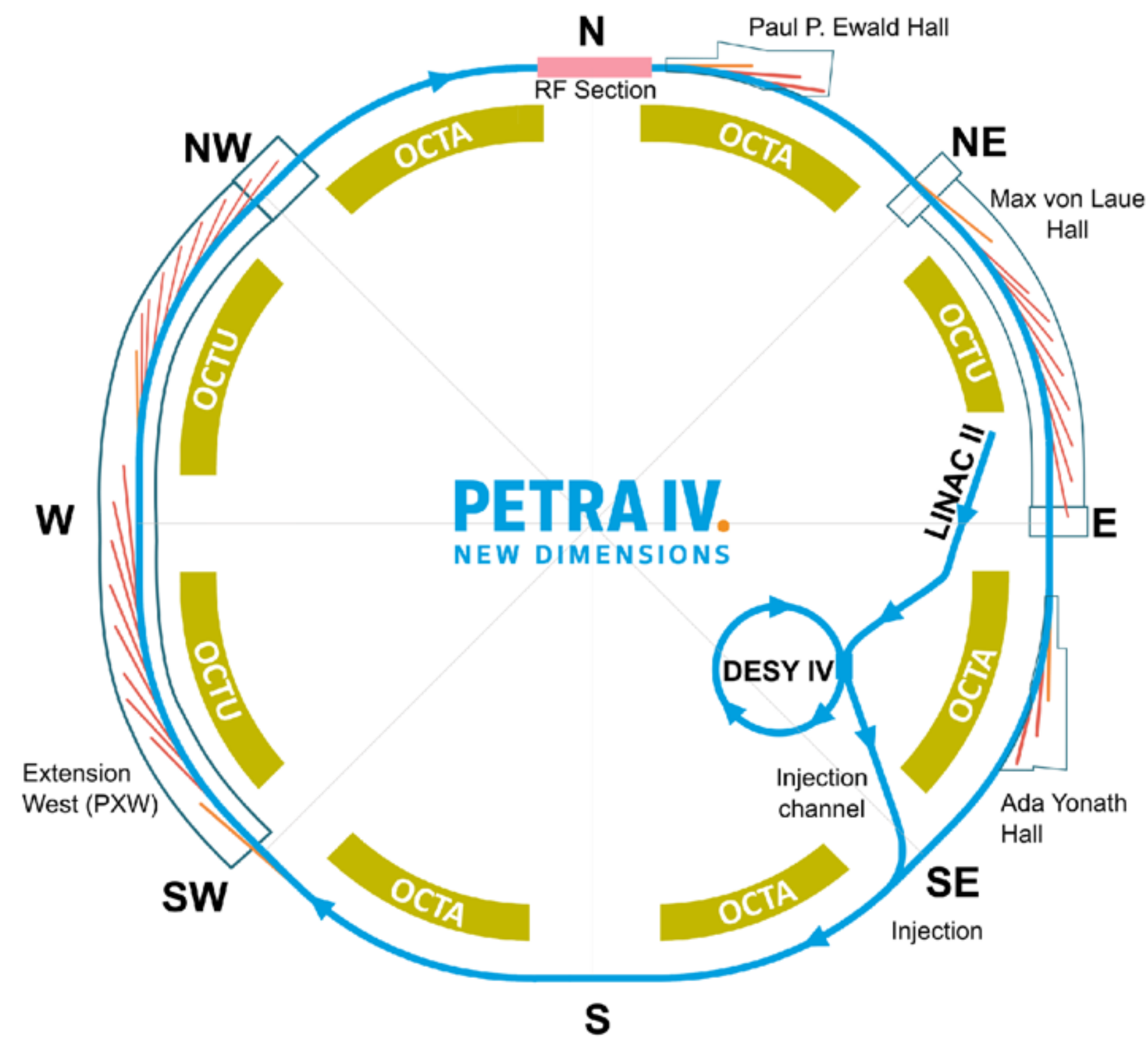
Current state of the art

- > GeV-scale beams from cm-scale plasmas
- > Percent-level energy stability & spread
- > A new accelerator cavity with every shot
- > Laser performance determines reproducibility and availability



DESYs PETRA IV Upgrade

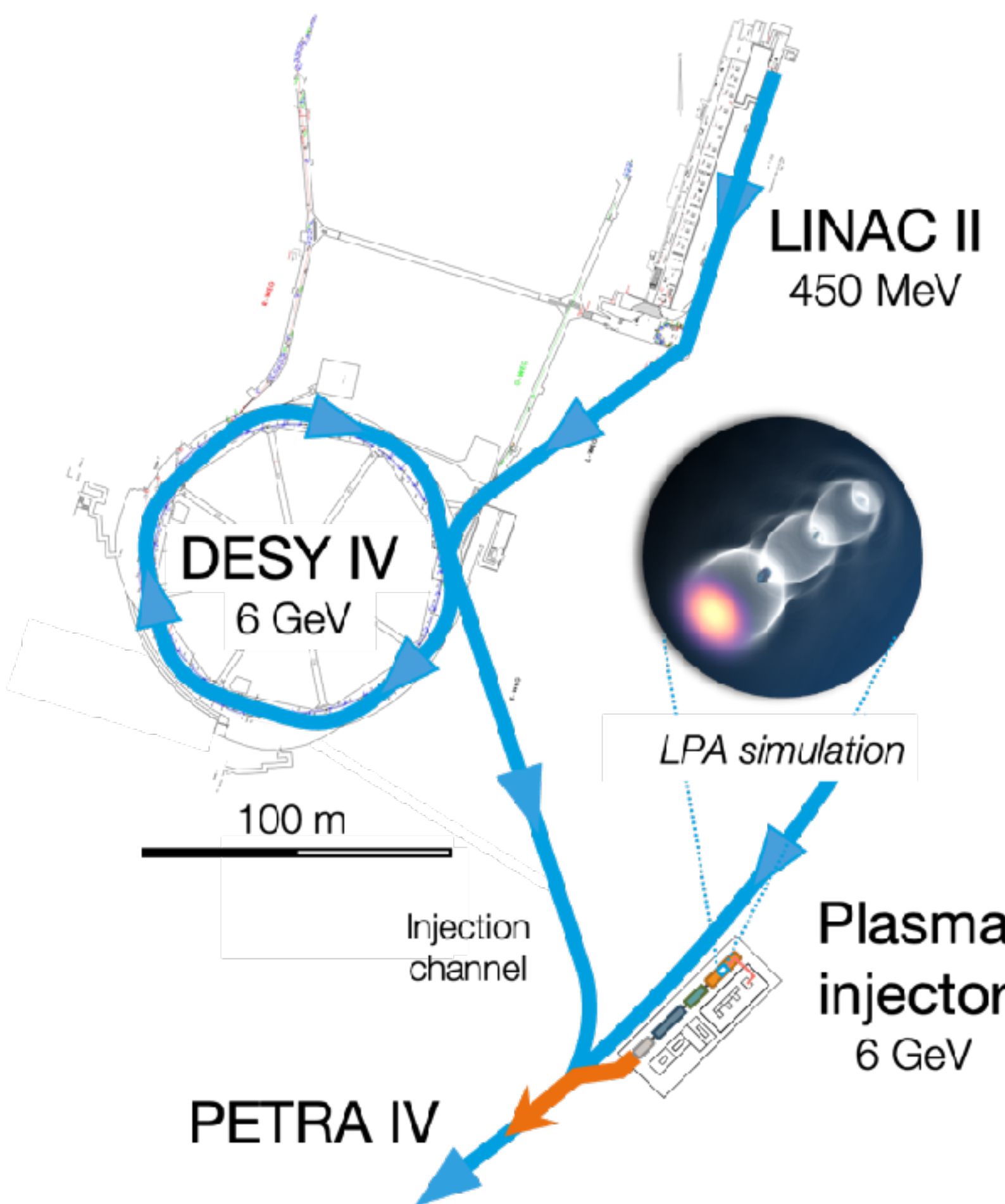
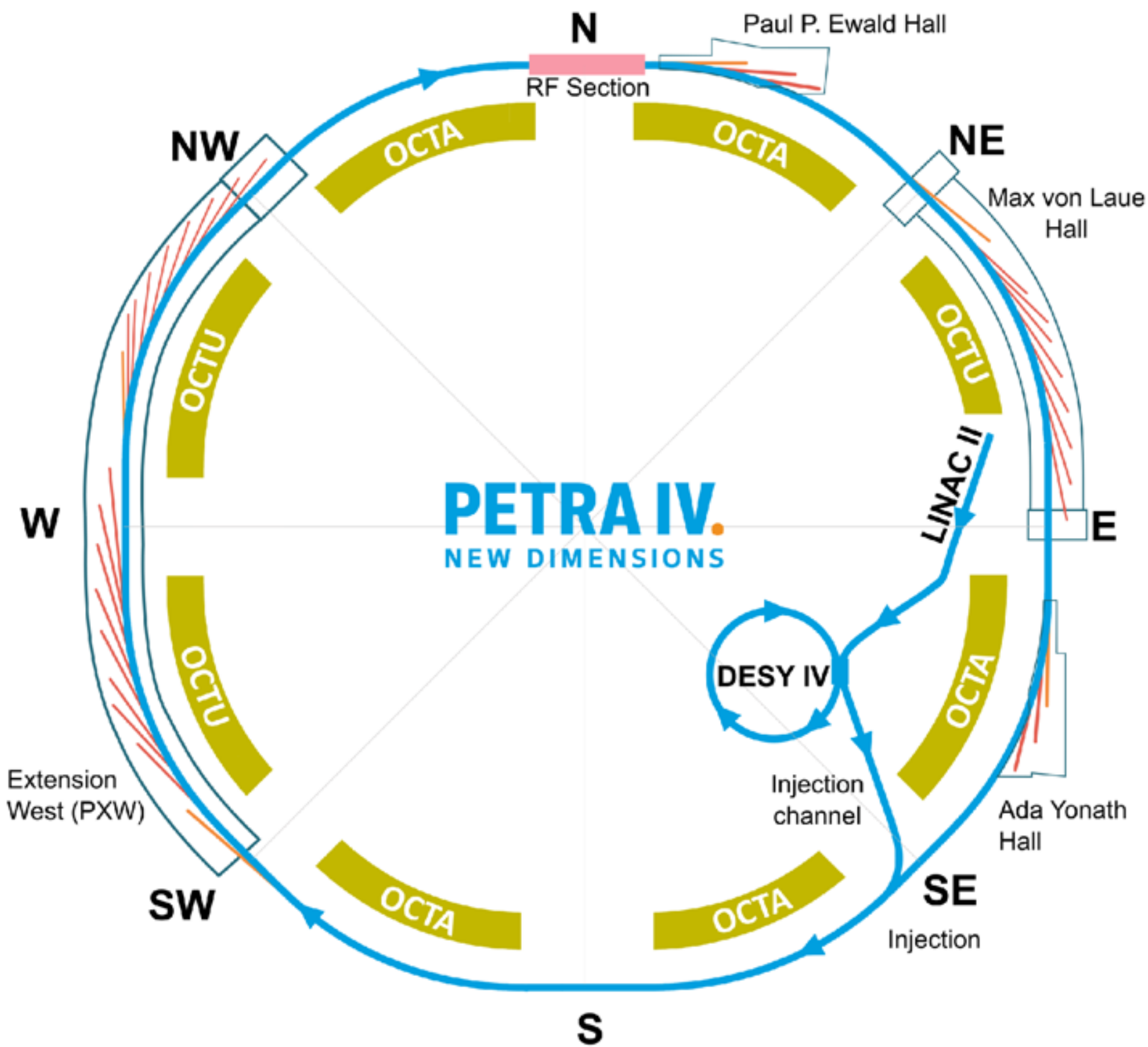
The ultimate 3D X-ray microscope



Plasma Injector for PETRA IV

Direct injection of 6 GeV electrons into the storage ring

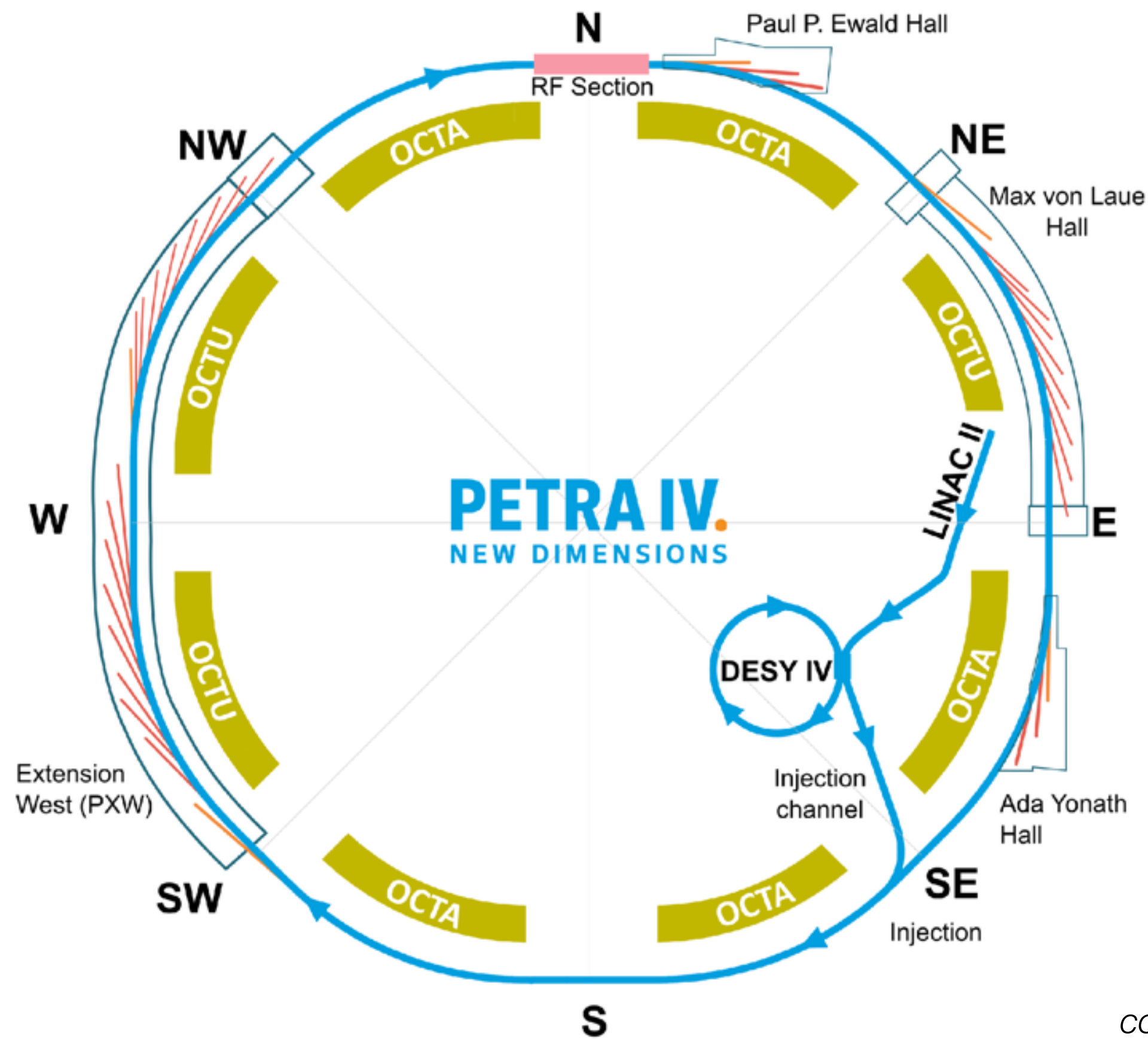
Credit: A. Martinez de la Ossa et al., PETRA IV Plasma Injector Conceptual Design Report



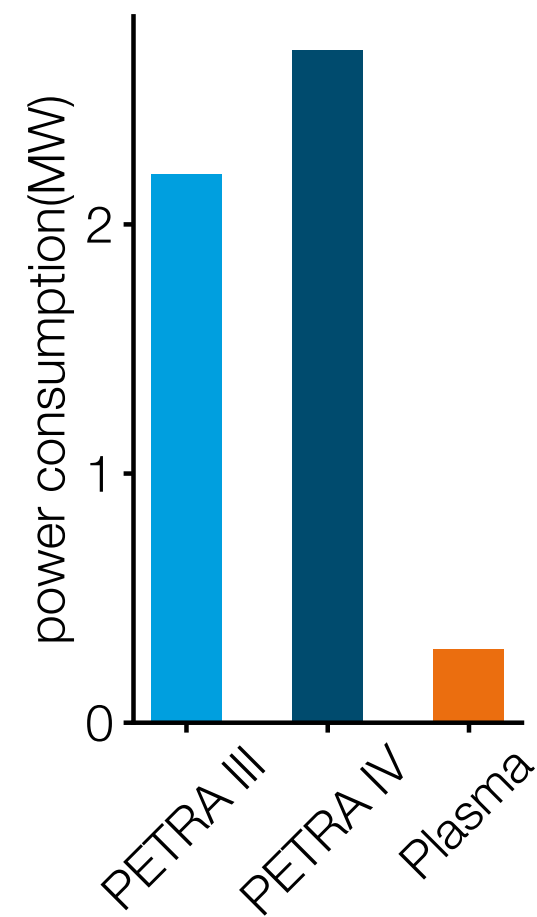
Plasma Injector for PETRA IV

Direct injection of 6 GeV electrons into the storage ring

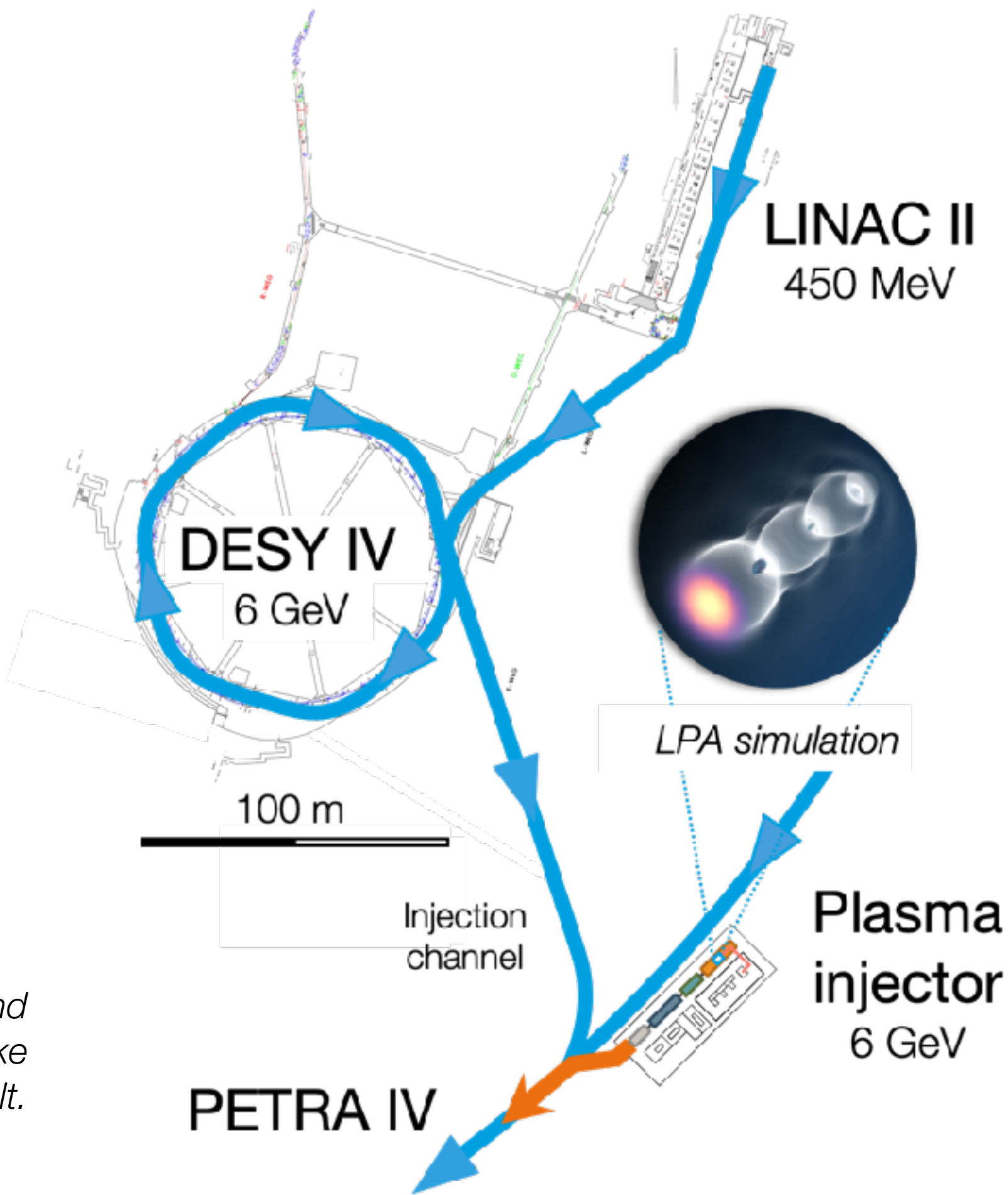
Credit: A. Martinez de la Ossa et al., PETRA IV Plasma Injector Conceptual Design Report



Injector power usage (during injection)



Power consumption estimates and comparisons are very complex, so take all our estimates with a grain of salt.



Plasma Injector for PETRA IV

Conceptual Design Report

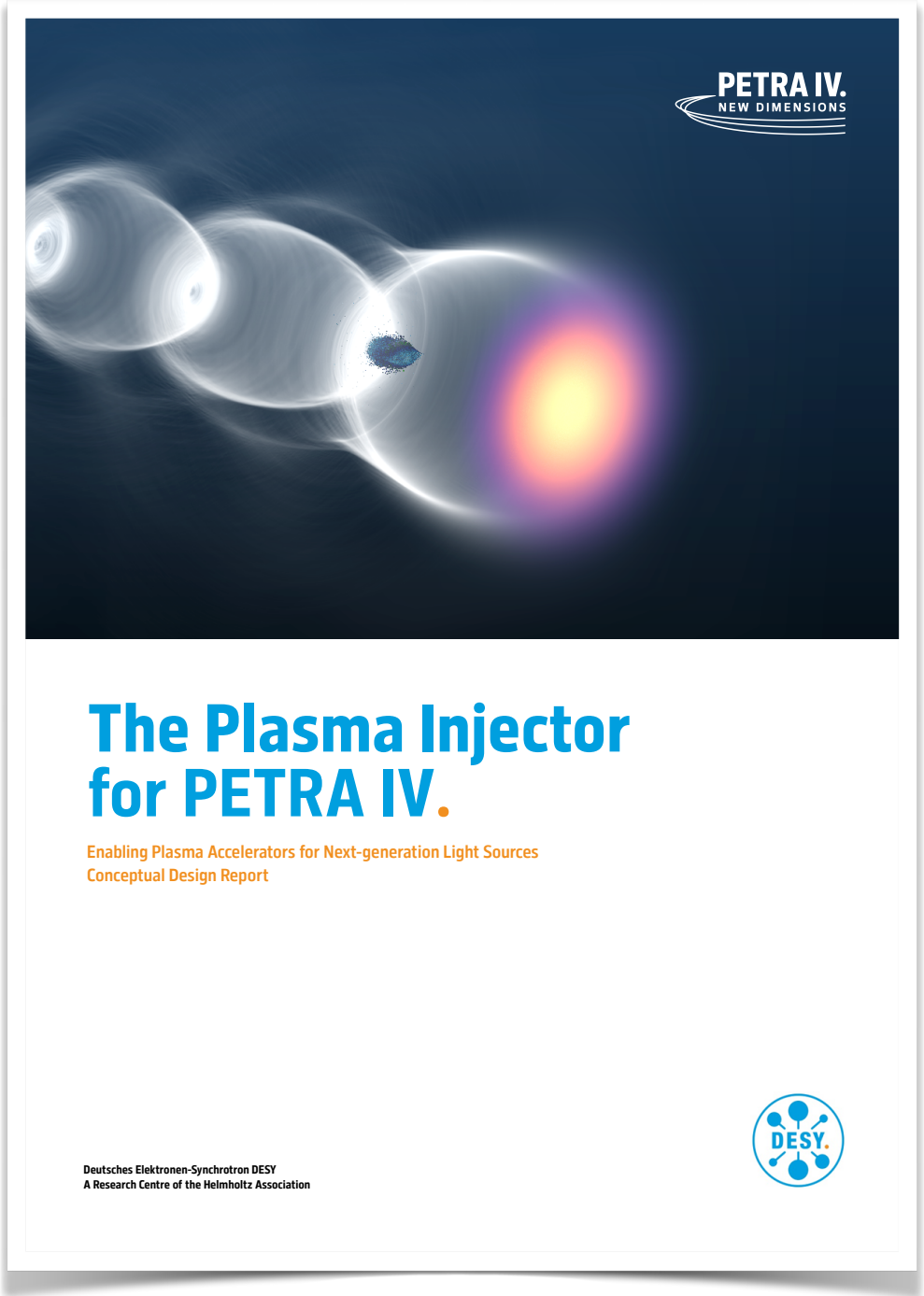
Credit: A. Martinez de la Ossa et al., PETRA IV Plasma Injector Conceptual Design Report

Requirements

- > Filling the ring (within 10 minutes)
- > Top-up operation (1% charge every 6 minutes)

Specifications

Beam Energy	6 GeV
Energy spread and Jitter	< 0.3%
Charge injection rate	> 2.6 nC/s
Availability	> 98%

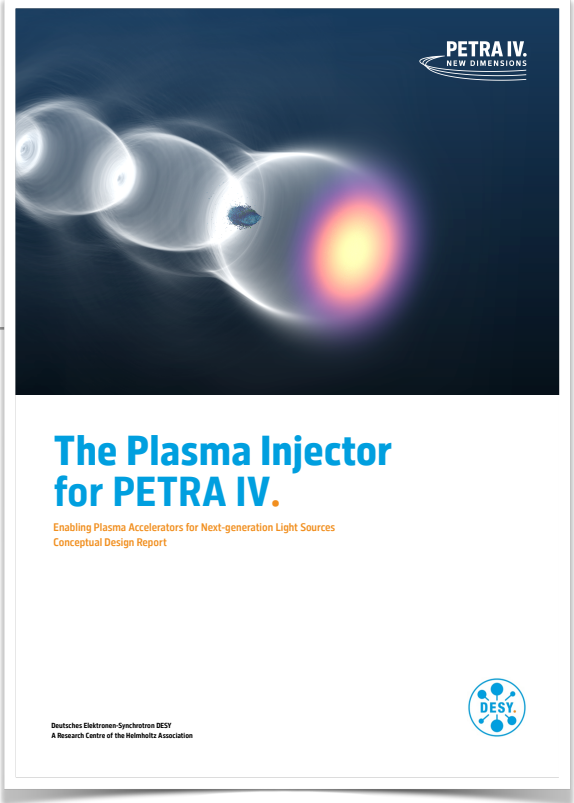
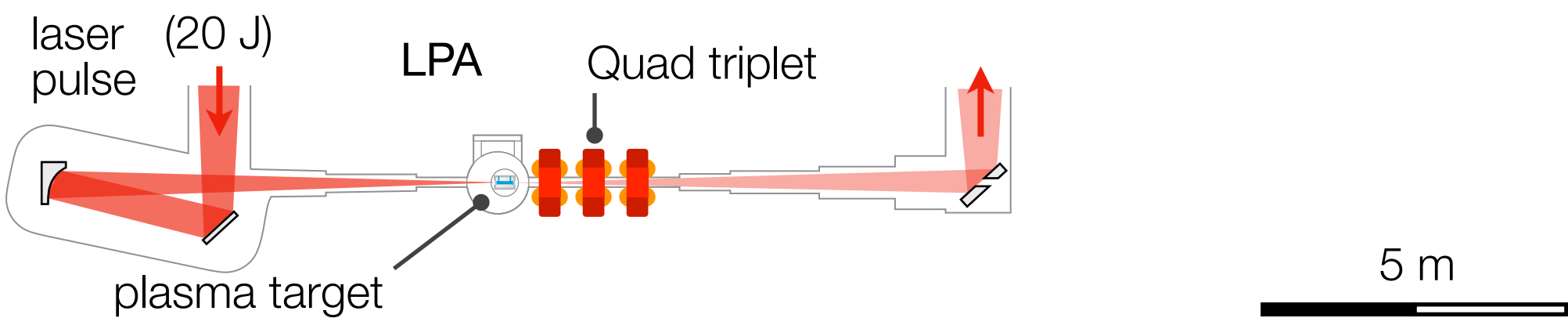


DOI: 10.3204/PUBDB-2024-06078
plasma.desy.de → publications

Plasma Injector for PETRA IV

Initial Plasma Stage

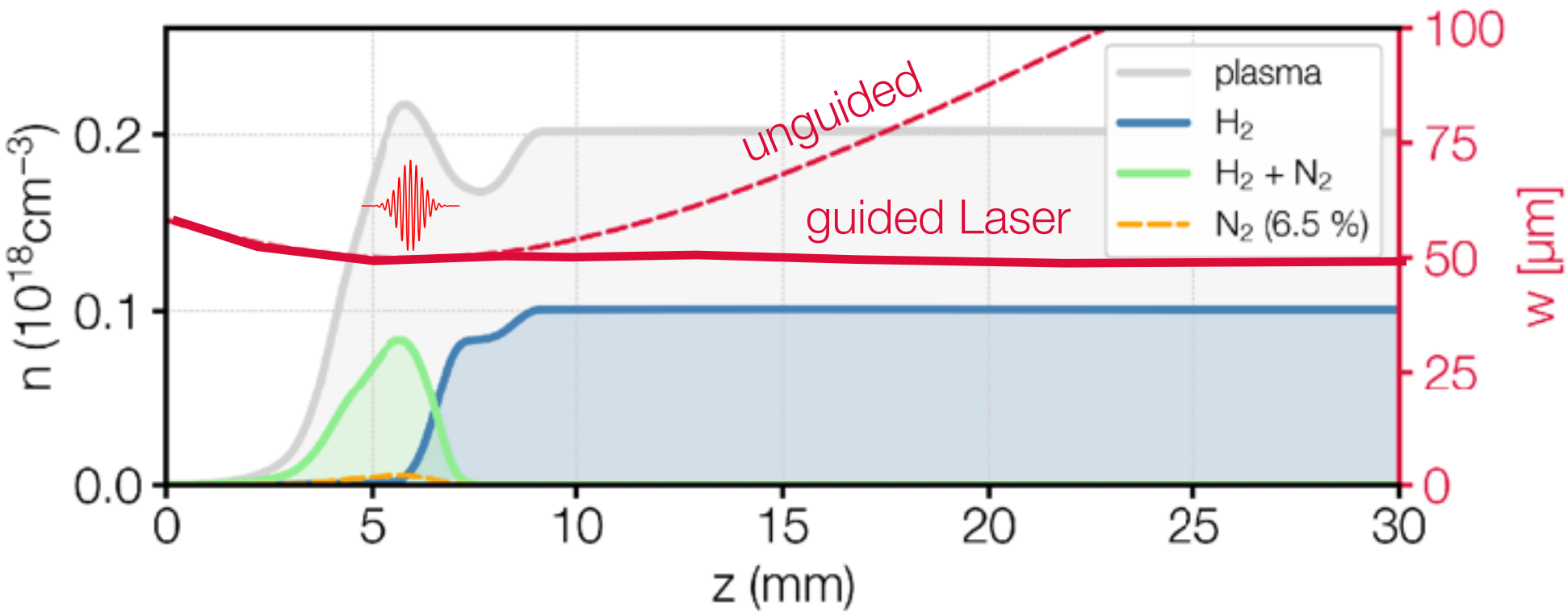
A. Martinez de la Ossa et al., The Plasma Injector for PETRA IV



Baseline parameters

(Subject to improvements)

Laser energy	20 J
Laser Power	350 TW
Energy	6 GeV
Energy spread	0.5 %
Charge	82 pC
Efficiency	2.7%



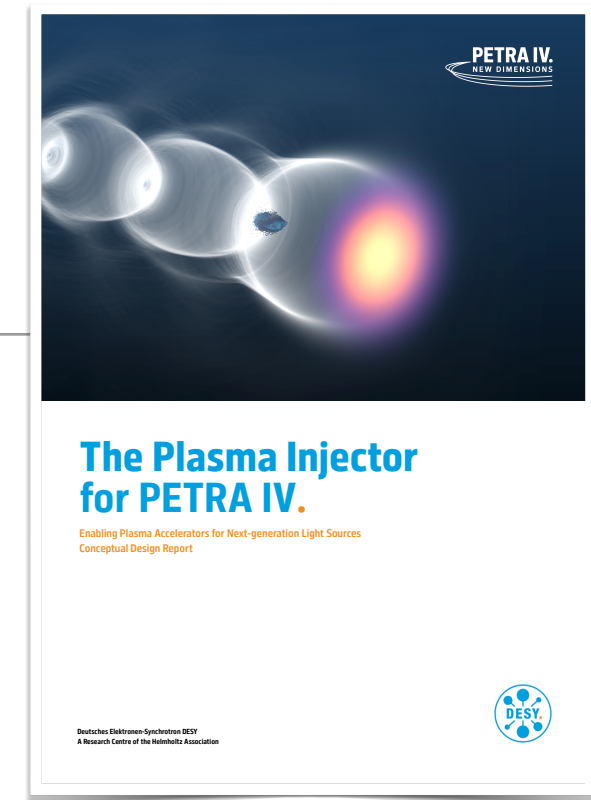
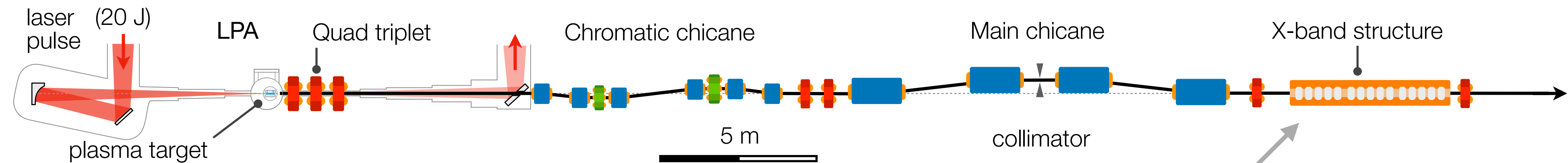
Plasma Injector for PETRA IV

Active Energy Compression

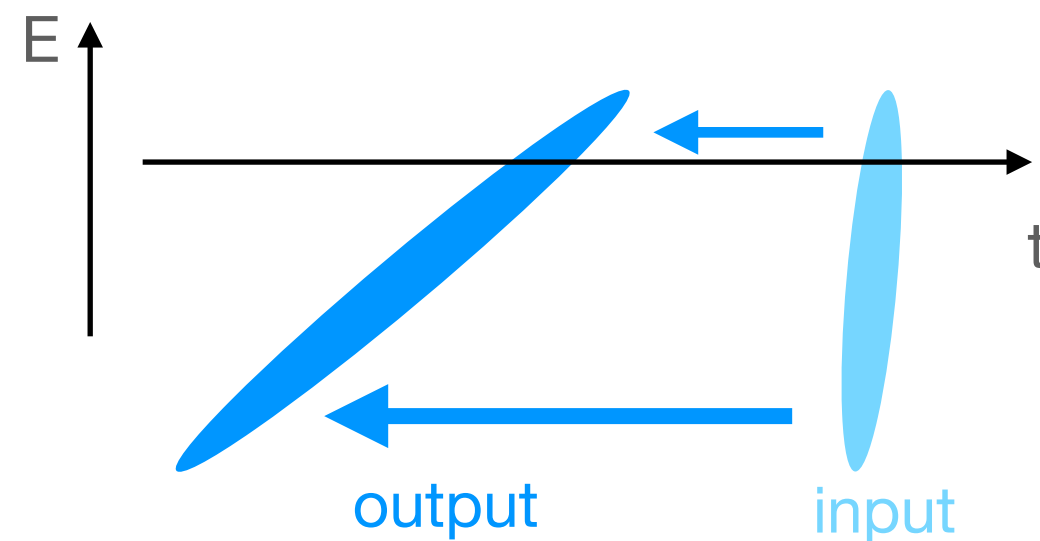
A. Ferran Pousa et al., PRL 129, 094801 (2022)

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

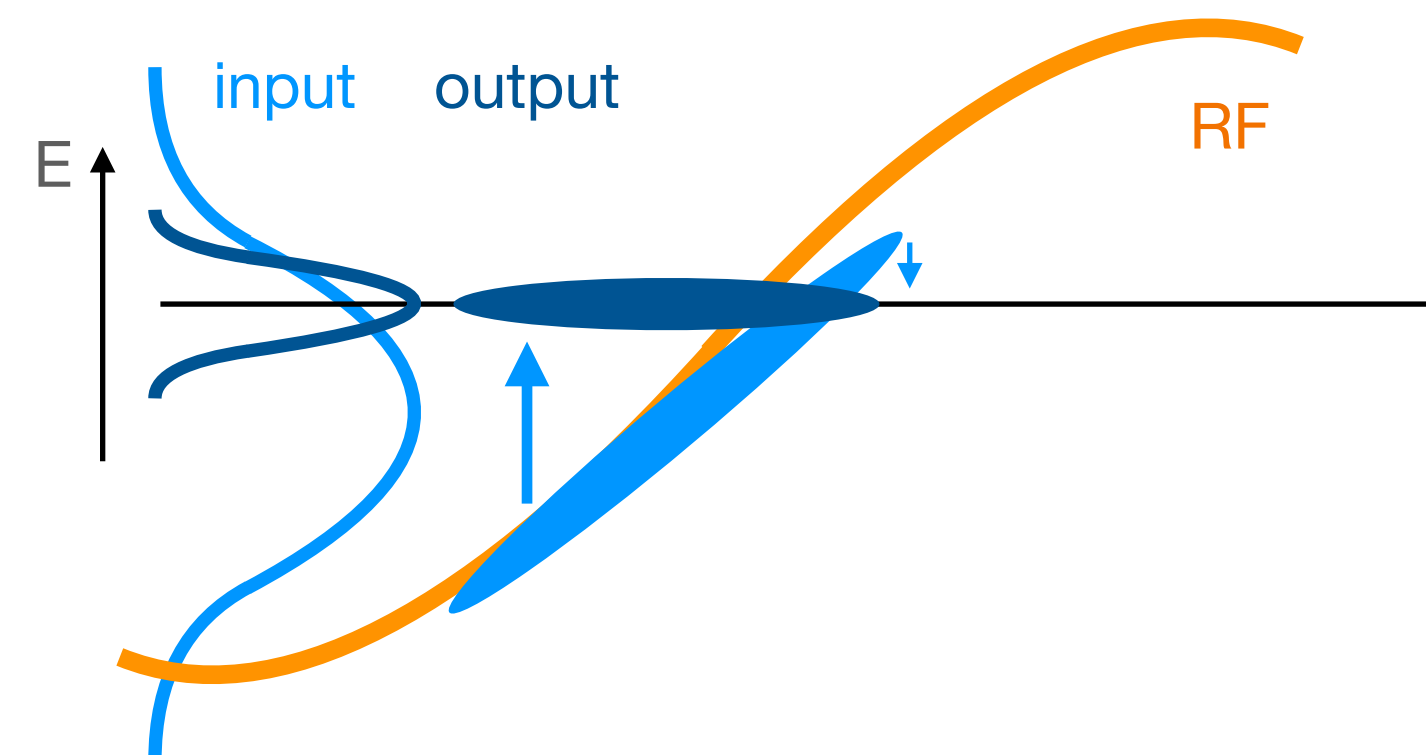
A. Martinez de la Ossa et al., The Plasma Injector for PETRA IV



Chicane introduces energy dependent delay



RF introduces time-dependent energy shift, effectively removing the energy spread and jitter

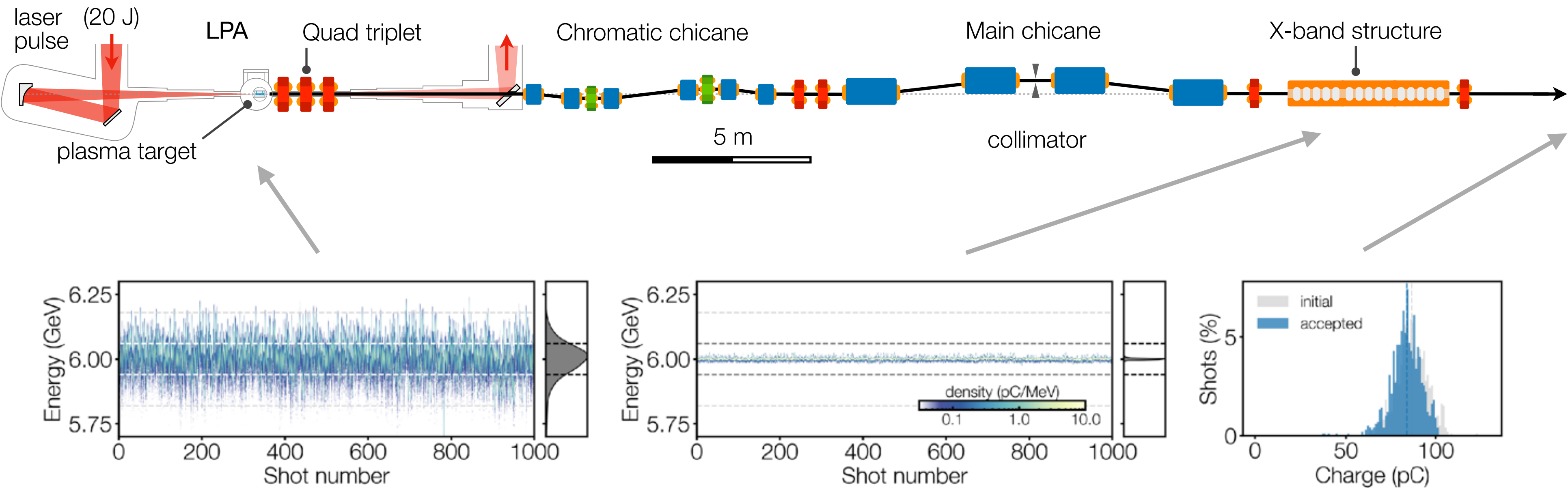
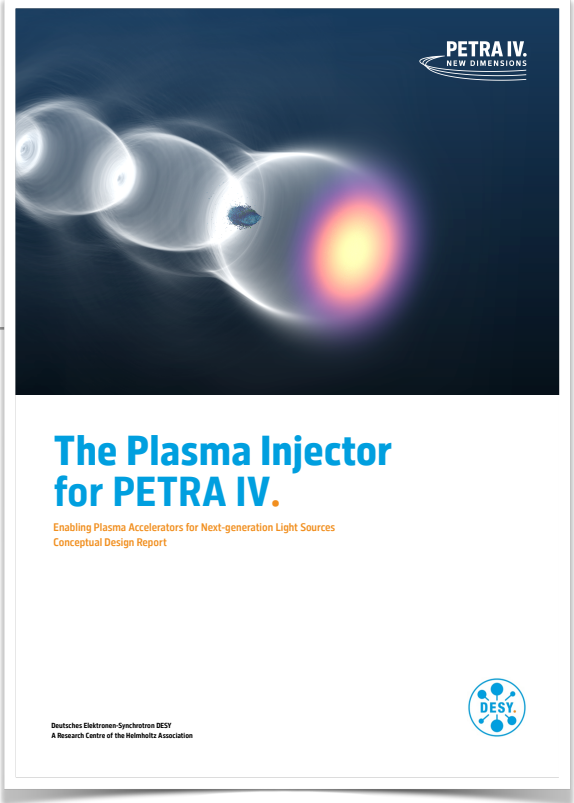


Plasma Injector for PETRA IV

Feasible with technology available today

A. Ferran Pousa et al., PRL 129, 094801 (2022)
S. A. Antipov et al, PRAB 24, 111301 (2021)

A. Martinez de la Ossa et al., The Plasma Injector for PETRA IV



Simulations include realistic jitters in laser energy, wavefront, RF phase and Laser-to-RF synchronisation

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

DESY is developing key technologies together with partners

Implementation Plan

requirements

charge rate

~10 minutes to fill

charge transmission

match ring acceptance

availability

Stable high average power laser system

repetition rate

30 Hz

pulse energy

20 J

pulse length

50 fs

KALDERA

Ti:Sa diode pumped

Stable laser guiding to 6 GeV

charge per shot

Order 100 pC

energy

6 GeV

LPA + HOFI

Optical Field Ionisation

Post-plasma energy compression

energy stability and spread

< 0.3 %

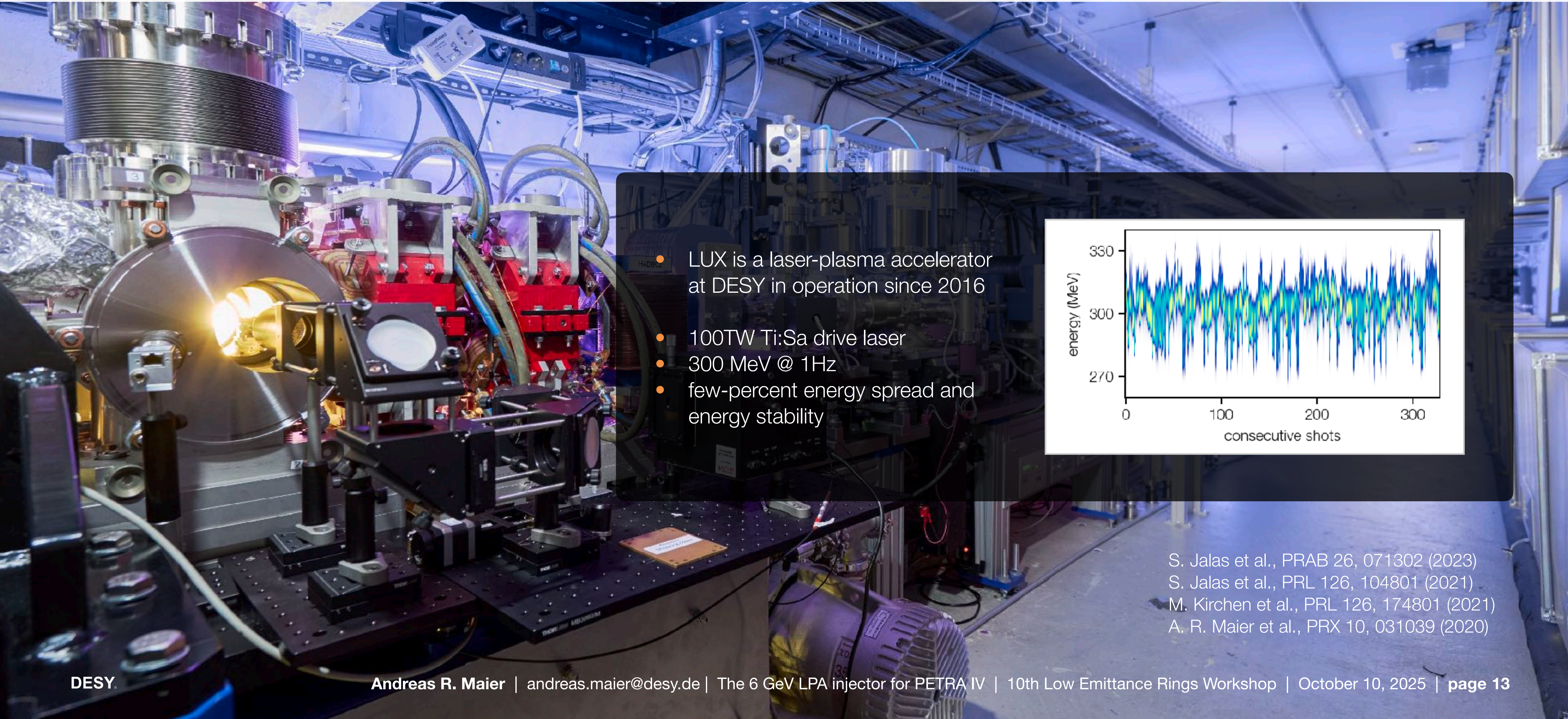
energy compression beamline

Implementation

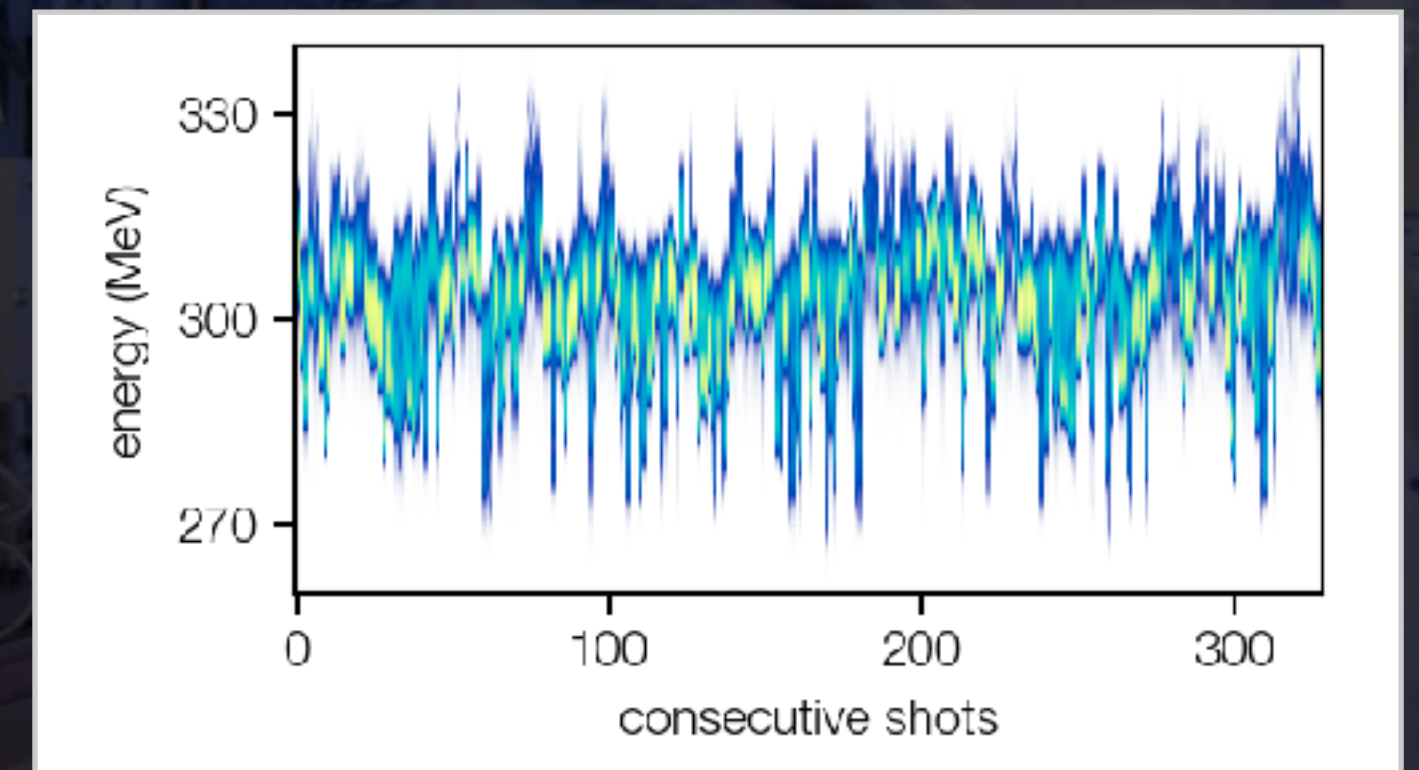
Energy Compression

Demonstrate Energy Compression

The LUX Laser-Plasma Accelerator at DESY



- LUX is a laser-plasma accelerator at DESY in operation since 2016
- 100TW Ti:Sa drive laser
- 300 MeV @ 1Hz
- few-percent energy spread and energy stability



S. Jalas et al., PRAB 26, 071302 (2023)
S. Jalas et al., PRL 126, 104801 (2021)
M. Kirchen et al., PRL 126, 174801 (2021)
A. R. Maier et al., PRX 10, 031039 (2020)

Demonstrate Energy Compression

Energy Compression Beamline at LUX



Decompression chicane



S-band RF cavity

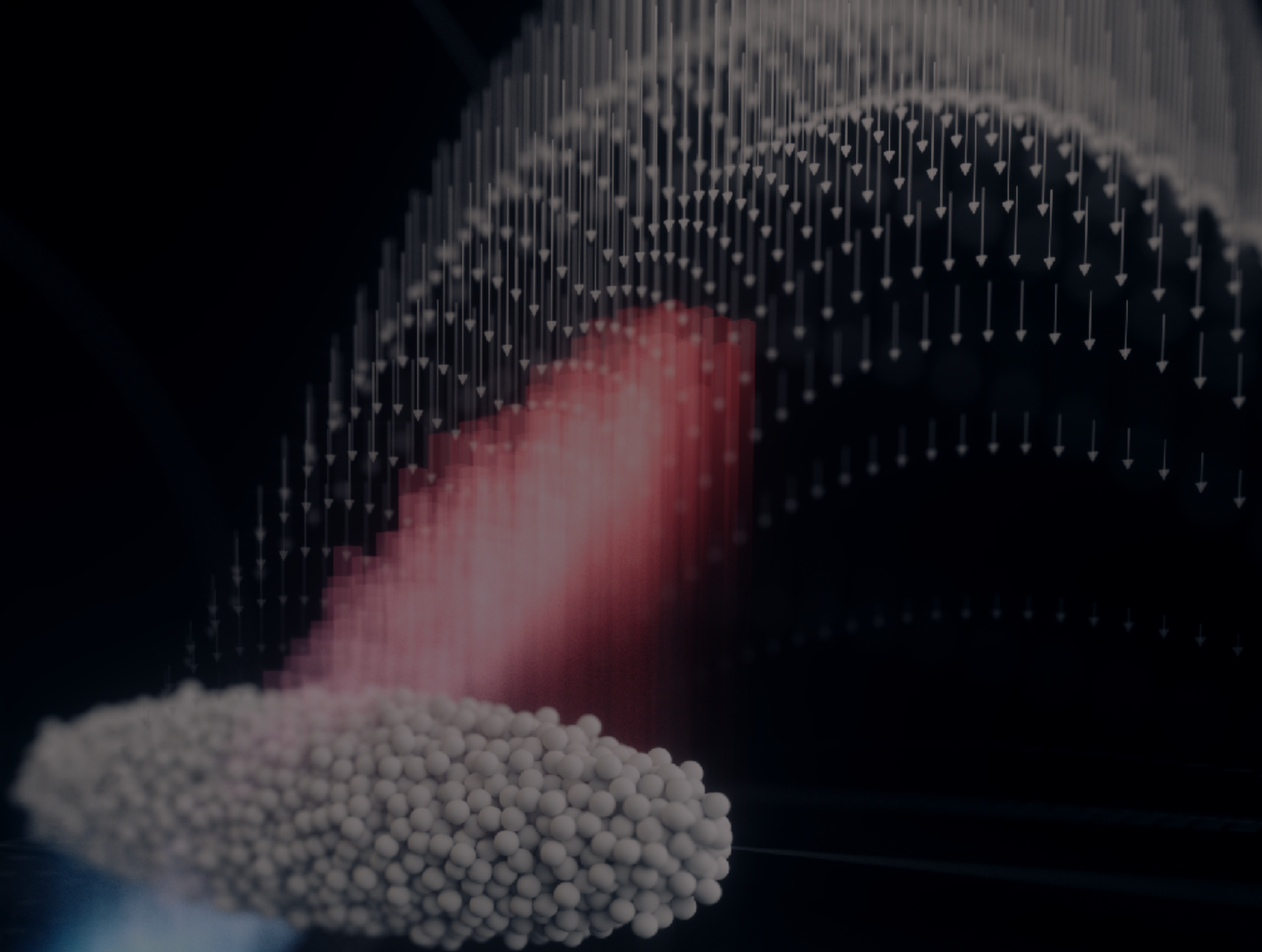
360° RF phase scan

energy spectrum is compressed
for a larger range of RF phases

S-band RF has a 10 cm
wavelength (3 GHz)

$$R_{56} = 10 \text{ cm}$$

$$V_{RF} = 45 \text{ MV}$$



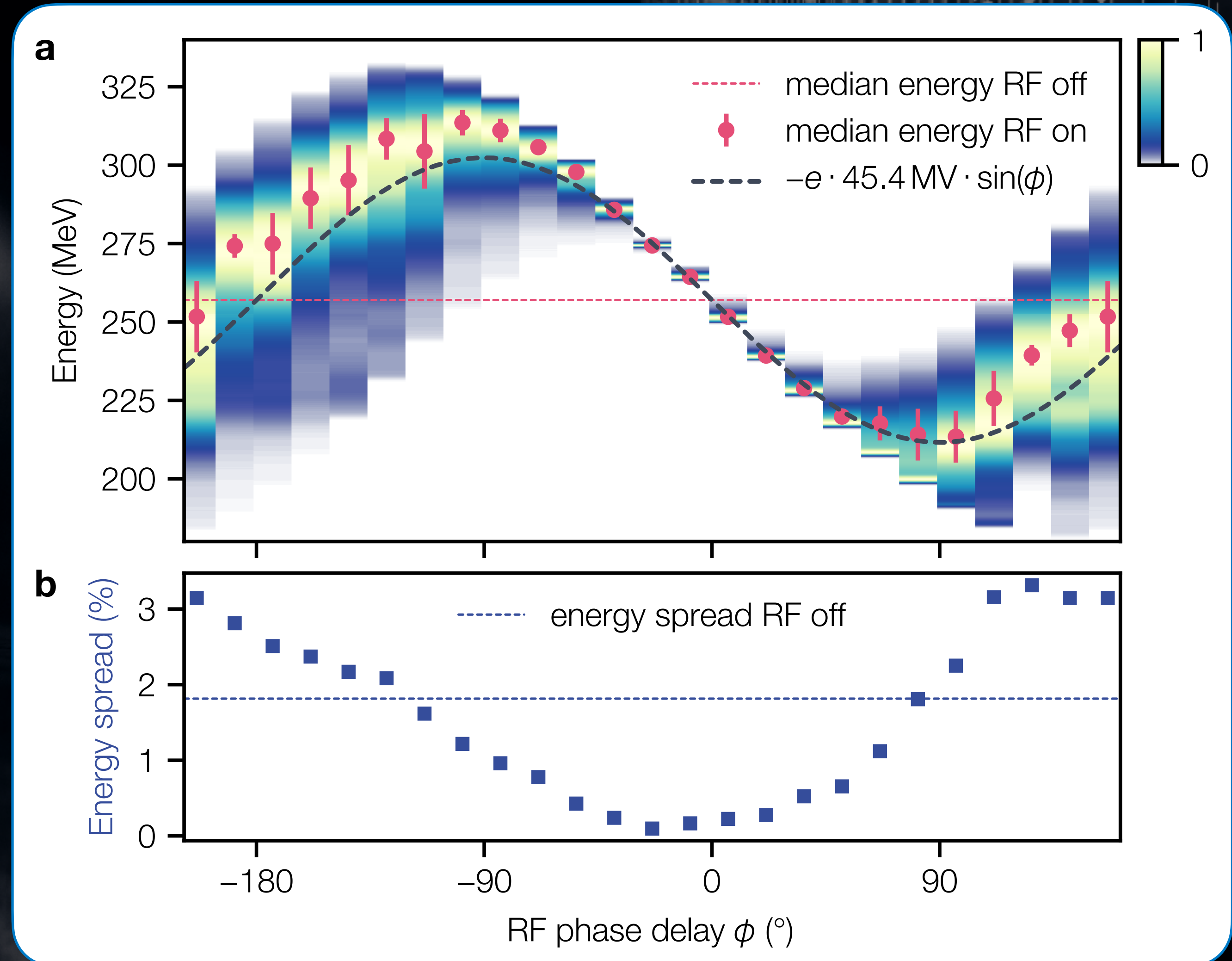
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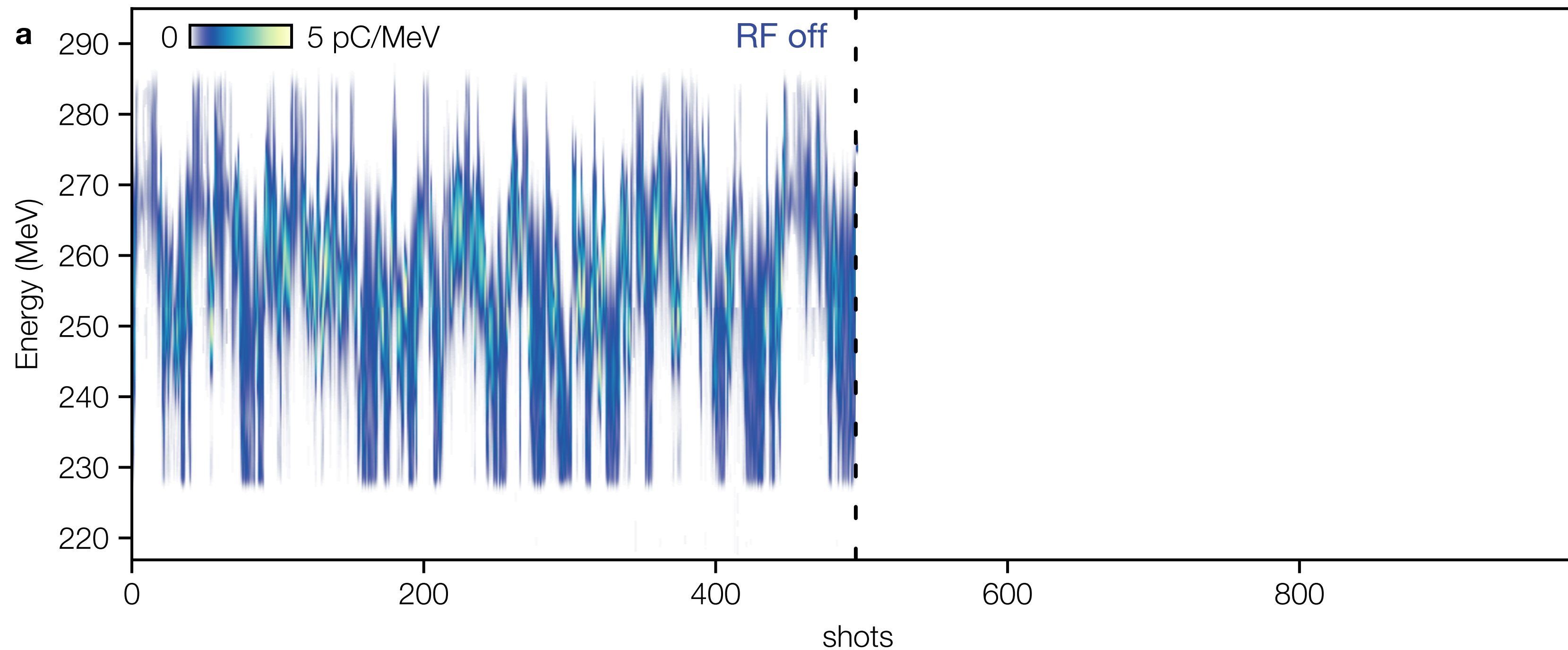
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P. Winkler et al. *Nature* 640, 907 (2025)

Demonstrate Energy Compression

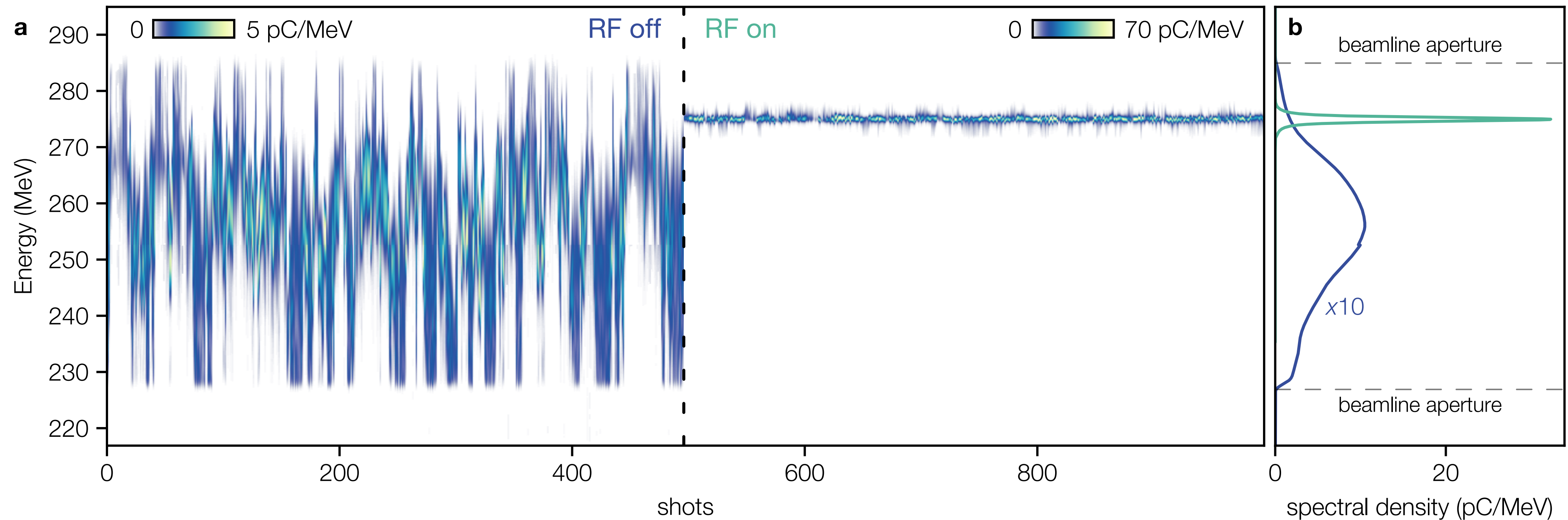
0.048% energy jitter & 0.097% energy spread, factor ~25 energy compression



P. Winkler et al. *Nature* 640, 907 (2025)

Demonstrate Energy Compression

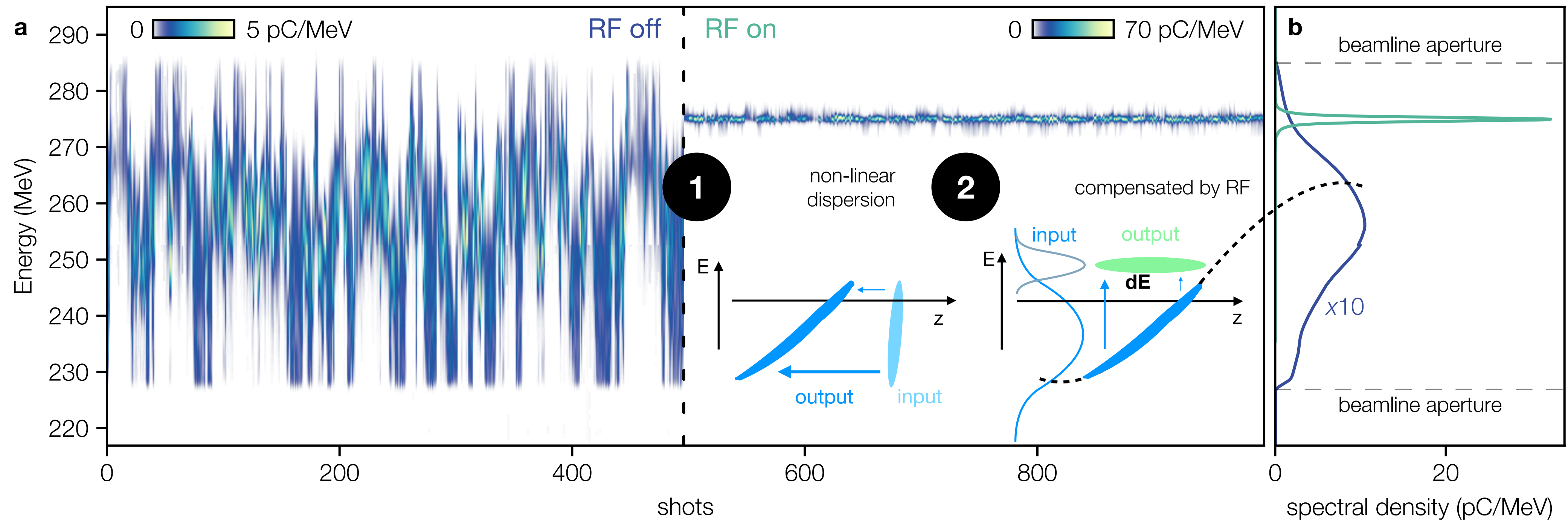
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P. Winkler et al. *Nature* 640, 907 (2025)

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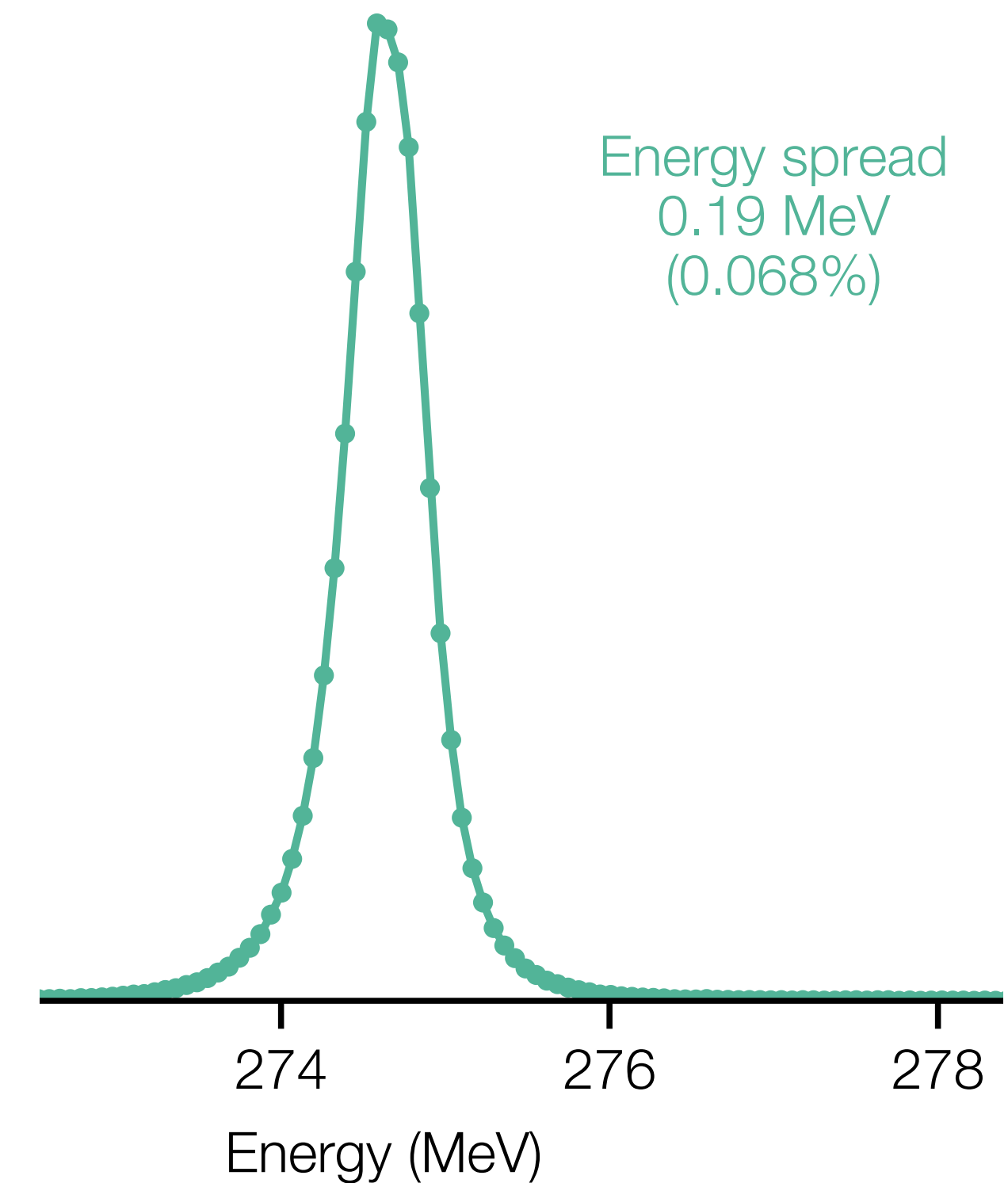
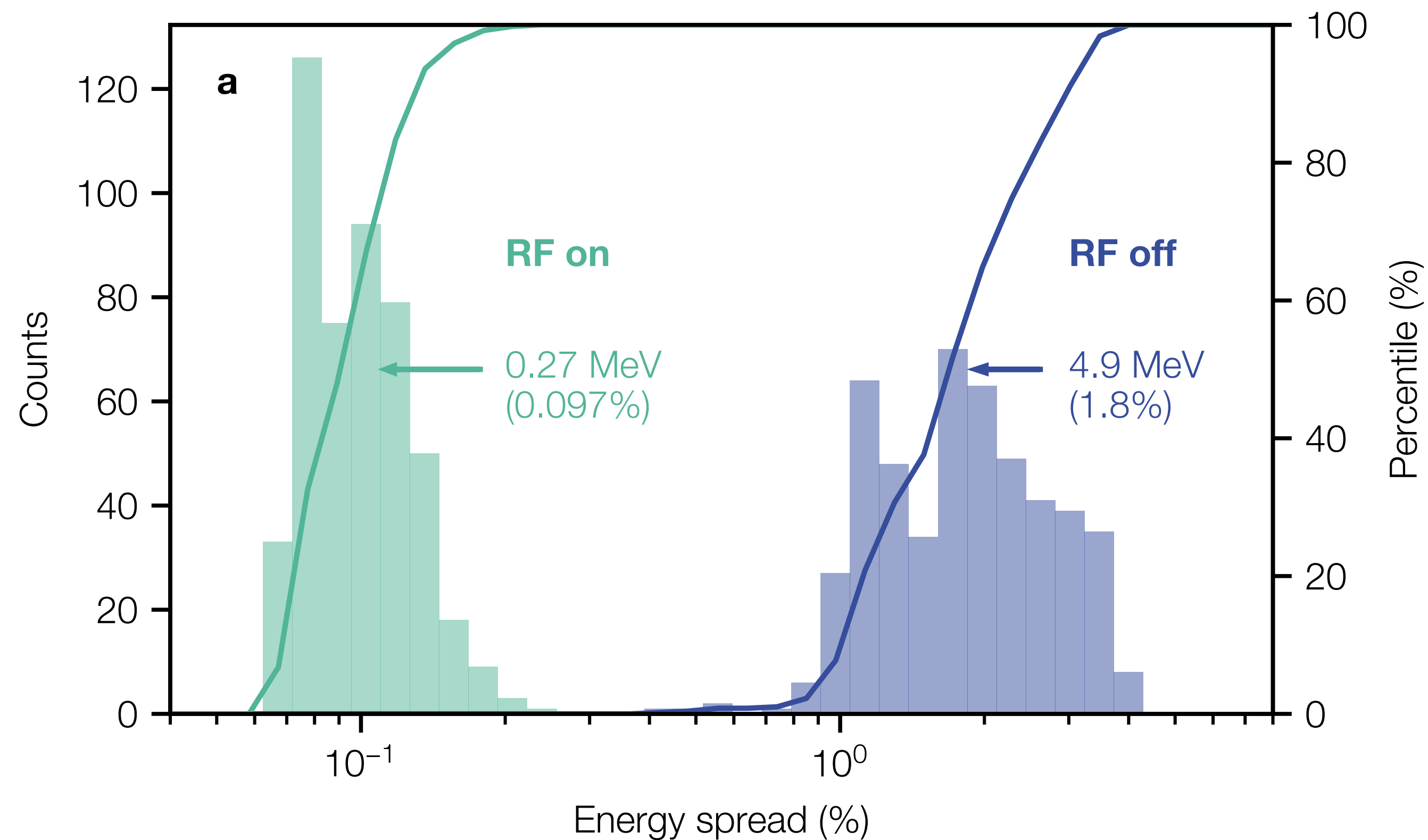
Non-zero RF phase compensates for non-linear dispersion



P. Winkler et al. *Nature* 640, 907 (2025)

Demonstrate Energy Compression

Energy spread is compressed to resolution limit of the spectrometer

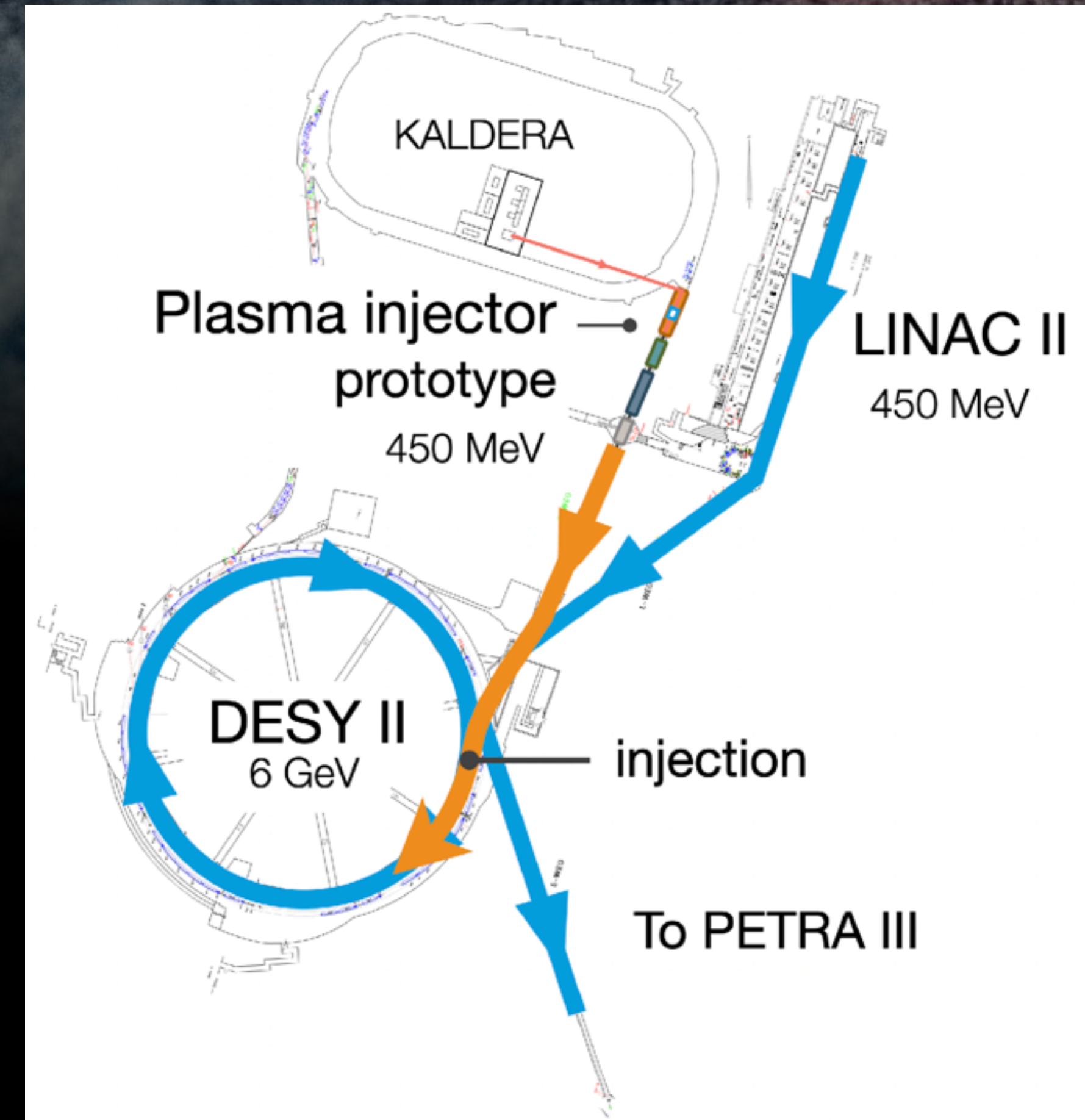


P. Winkler et al. *Nature* 640, 907 (2025)

Next: Demonstrate full technology chain at lower energy

Injection of LPA beams into the DESY II booster ring

- Demonstrate full technology chain (including synchronisation, matching, diagnostics, ...) at lower energy (~ 400 MeV)
- BMBF-funded 15M€ projects started 2025
- First experiments expected for 2026

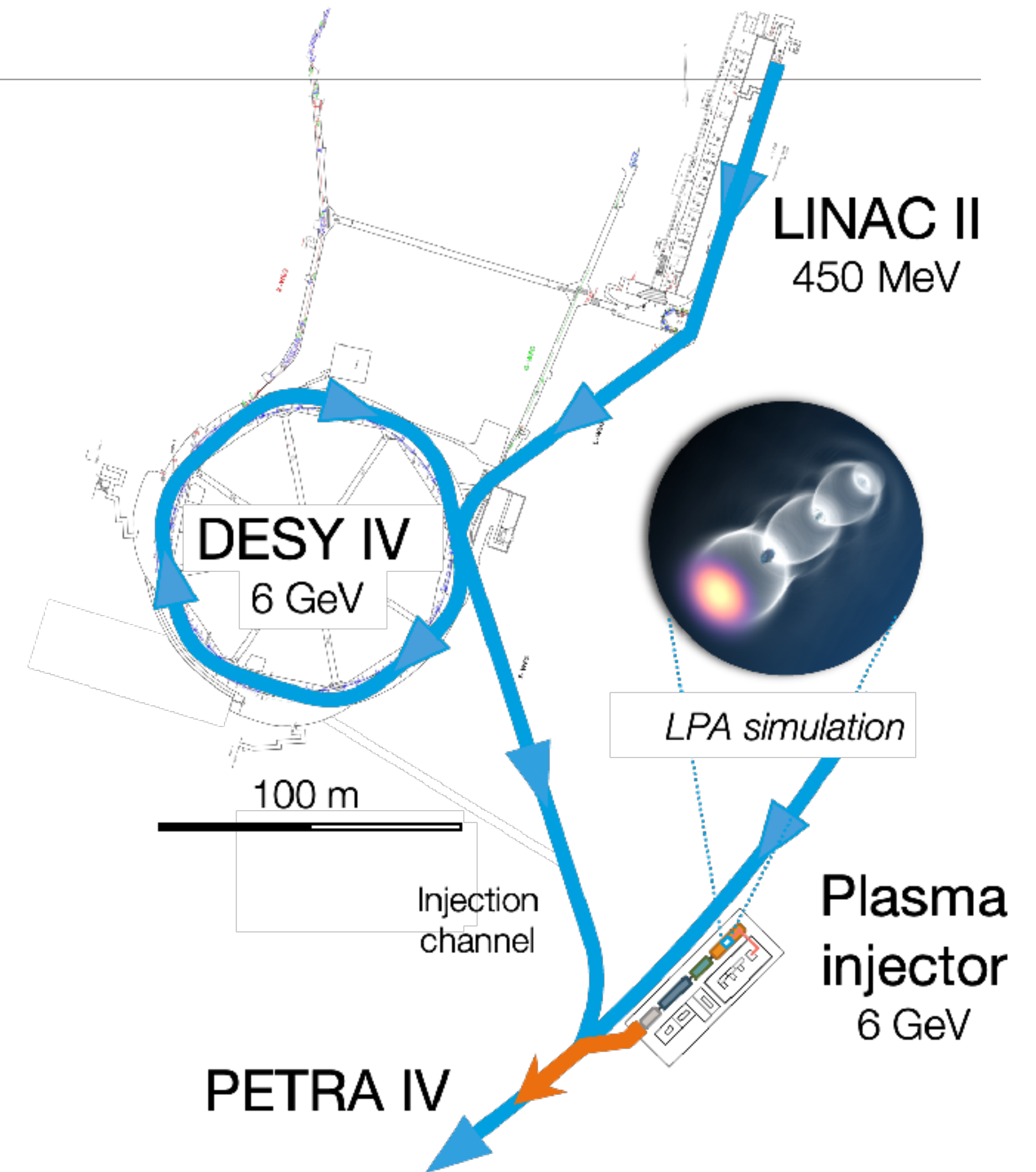


What's next

A few comments

Laser Technology

- > Lasers are the main concern w.r.t. availability
- > We think, a reliable high-power laser can be built, if done correctly
- > We closely follow the developments in the laser-based fusion community
 - > An industrial ecosystem could emerge that can supply reliable, high energy laser systems
 - > We could likely use the same lasers
 - > We are evaluating systems together with industry
- > We have launched a program to assess technological maturity of today's laser architectures



What's next

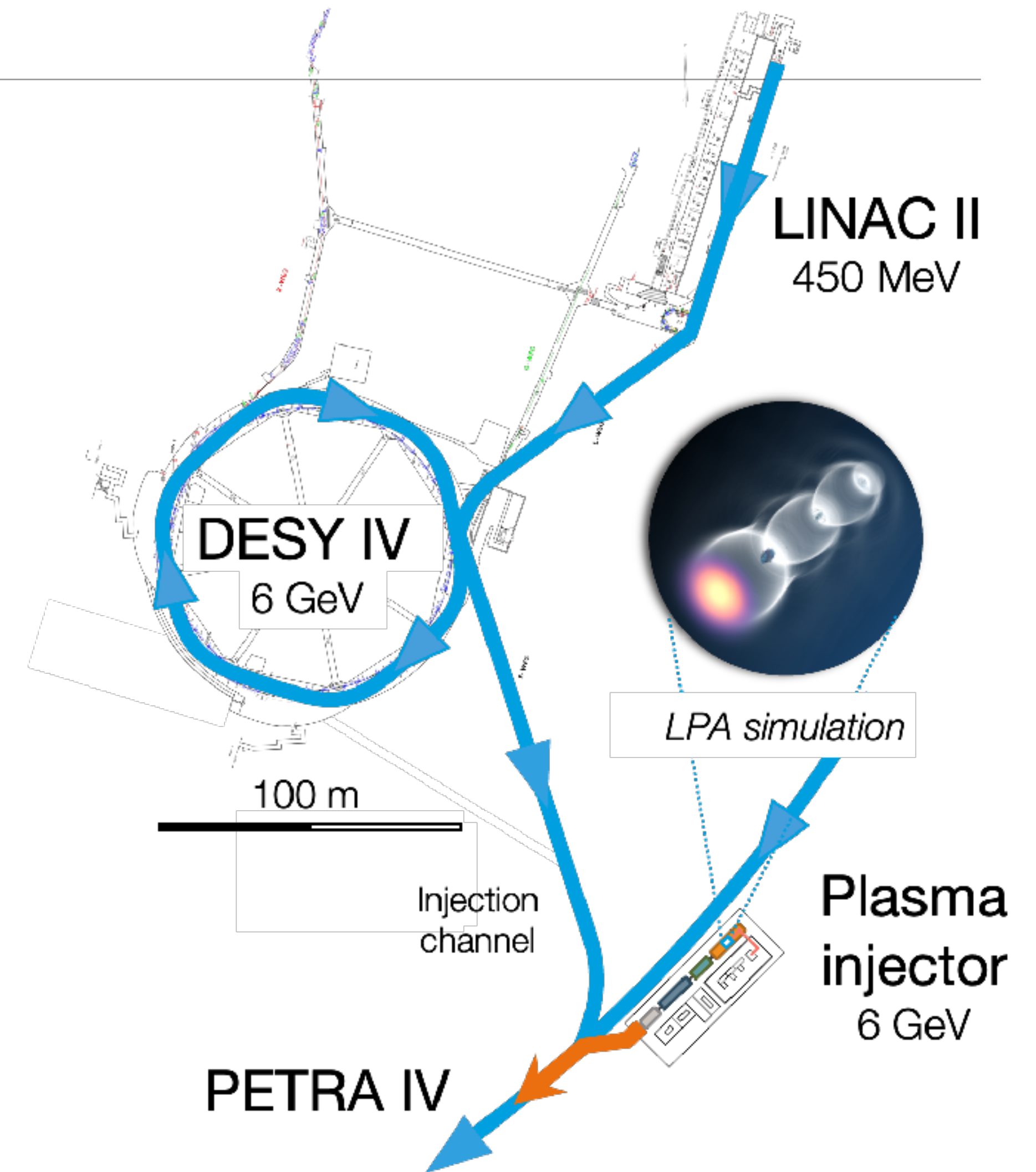
A few comments

Guiding

- > Recent results have shown 10GeV-class electron beams from an LPA
Phys. Rev. Lett. 133, 255001 (2024)
- > But guiding to 6GeV certainly is a challenge
- > We have a dedicated research program to get us there

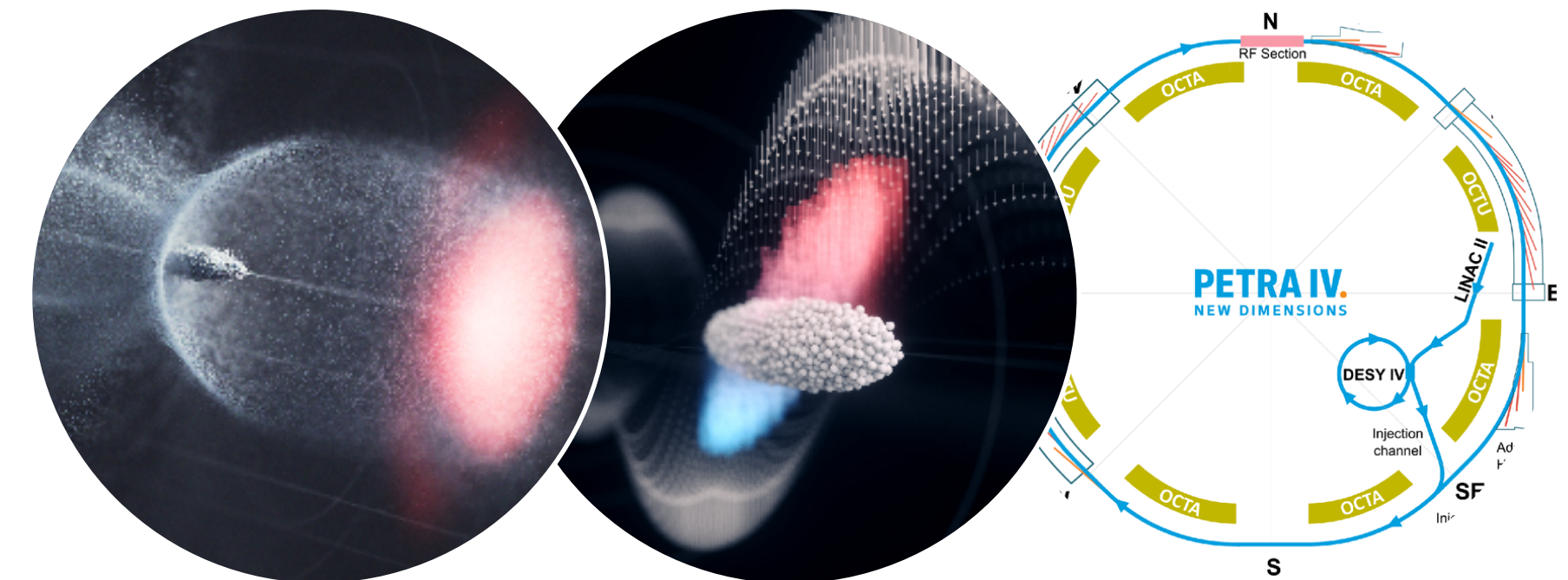
Beam physics

- > We are studying different working points and tolerances, also to address diagnostic challenges (resolution of low-charge BPMs)
- > There is much to say about beam physics, and the excellent work by Alberto, Sergey, Ilya, Riccardo and others.
- > We are looking into commissioning based on LPA beams
See S. Antipov, EAAC2025 Conference



Conclusion

- > Synchrotron injection might be the first application of an LPA because:
 - > comparably low rep rate
 - > moderate requirements on energy spread and emittance
 - > Energy compression exploits ultra-short bunch length
 - > Compactness: less real-estate and operations cost
- > PETRA IV will feature a dedicated building with an LPA for direct injection
- > Baseline injector technology is a refurbished LINAC II + DESY IV
- > But do we really need DESY IV? We are evaluating to go with plasma only right from the start (decision by early 2027)



The DESY plasma group

See our webpage at plasma.desy.de for the full team

Wim Leemans
Division Director



Photo: Marta Mayer (DESY)



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Group Leader

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Thanks

To the whole plasma crew at DESY and the
many colleagues and groups from DESY
supporting this challenging project

Fig: SciCom Lab

