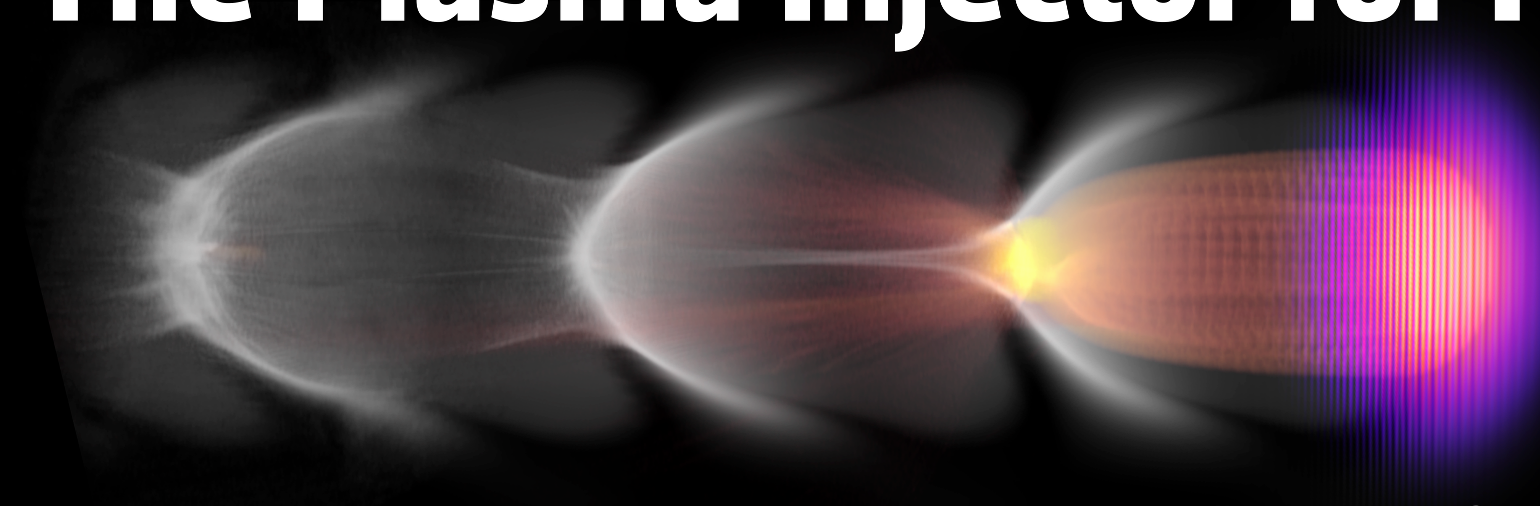
The Plasma Injector for PETRA IV



Conceptual Design Report

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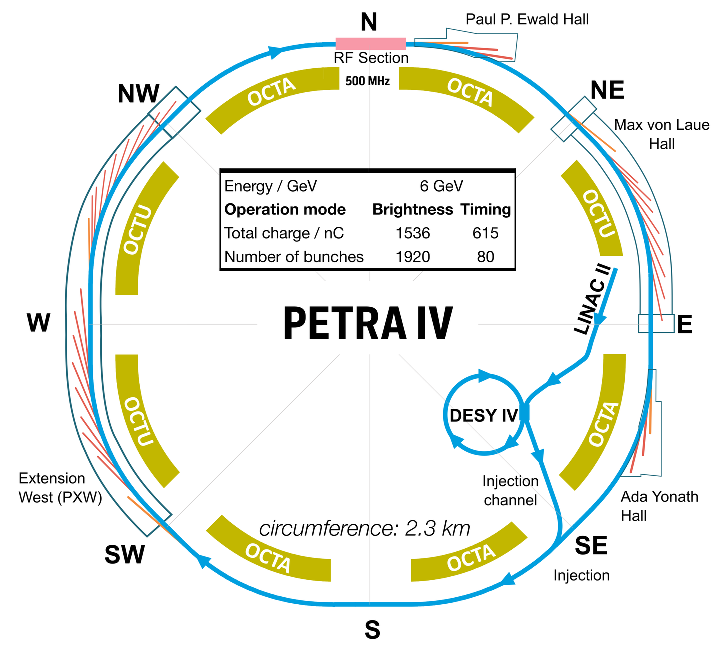
PETRA IV. The Ultimate 3D X-ray Microscope

The future 4th generation synchrotron light source at DESY

- PETRA IV will provide up to 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.



DESY's moonshot

Enabling laser-plasma accelerators for PETRA IV (and beyond)

- Builds upon successful LPA development at DESY: LUX for enhanced beam quality [1, 2], reliability and performance [3]
- Active feedback with AI control for enhanced stability: KALDERA [4]
- Laser guiding technologies for efficient 6 GeV energy gain: HOFI [5]
- State-of-the-art computing capabilities for precise modeling [6] and advanced machine learning optimization [7]
- Novel Energy Compression Beamline (ECB), enabling sub-per-mille levels of energy spread and stability [8, 9]

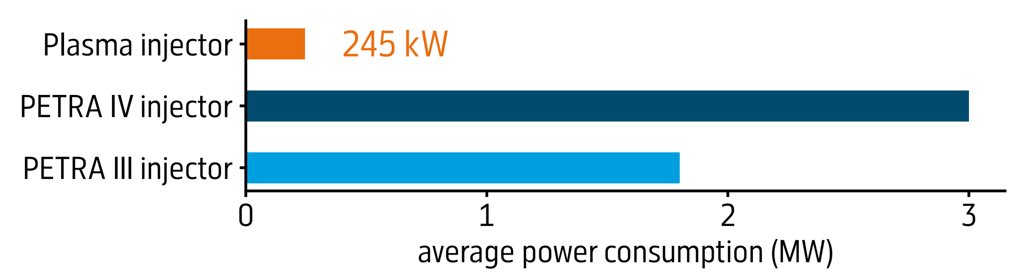
The Plasma Injector for PETRA IV

A competitive, compact and cost-effective alternative

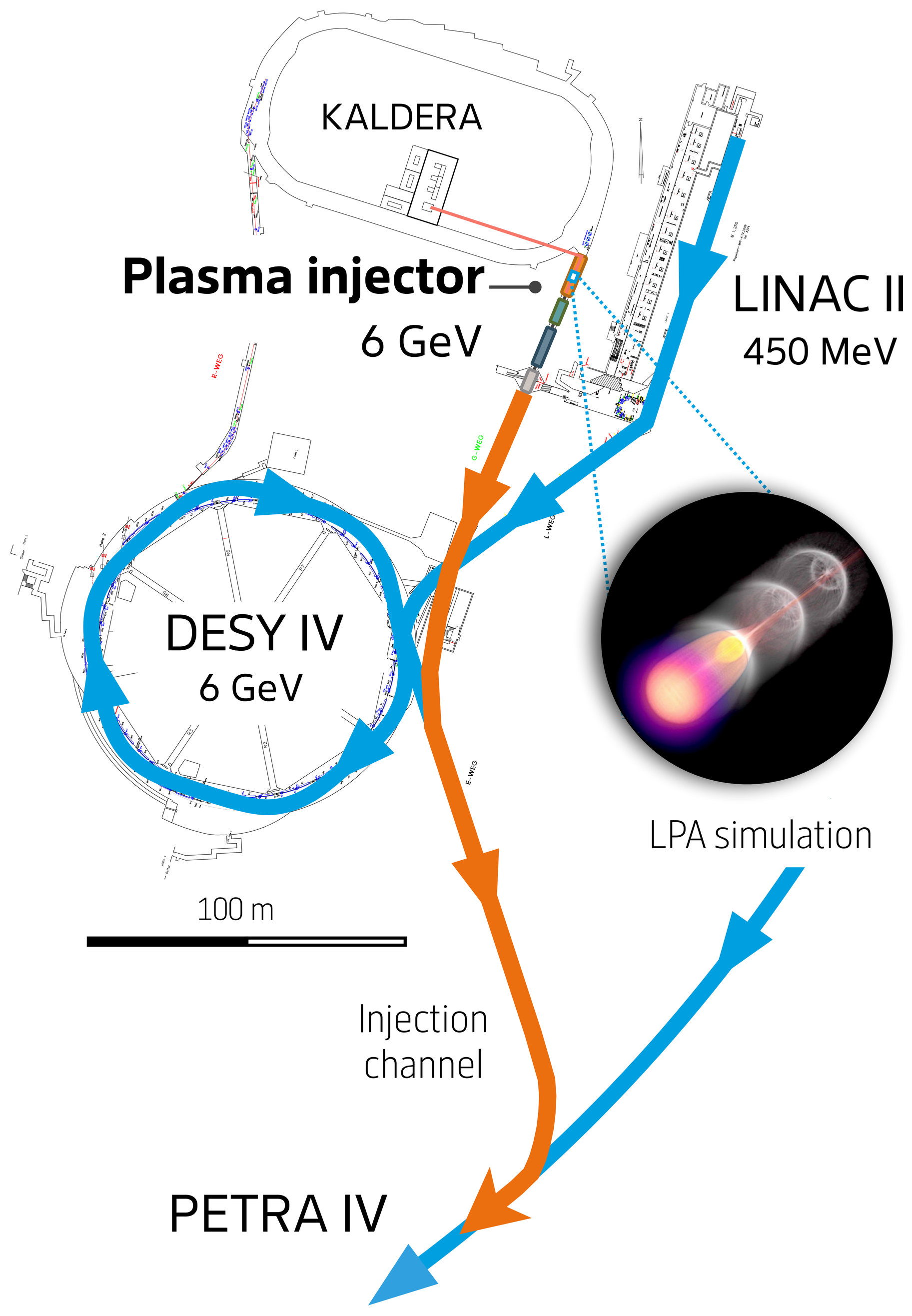
- **Competitive:** full PETRA IV operation (fill + top-up)
- **Compact:** laser-plasma acc. + beamline: < 50 m
- **Cost-effective:** power consumption: < 500 kW

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 the user's satisfaction)

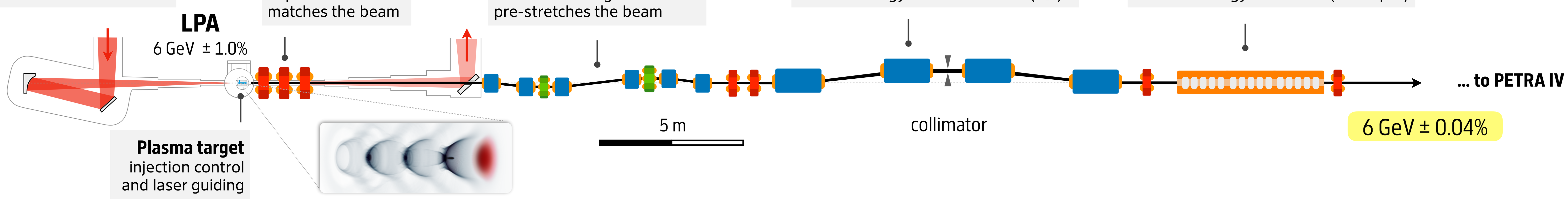


Laser-plasma acceleration technology (LPA) enables a more compact and energy efficient injector



Plasma injector design

Laser-plasma accelerator plus energy compression beamline



Simulation framework

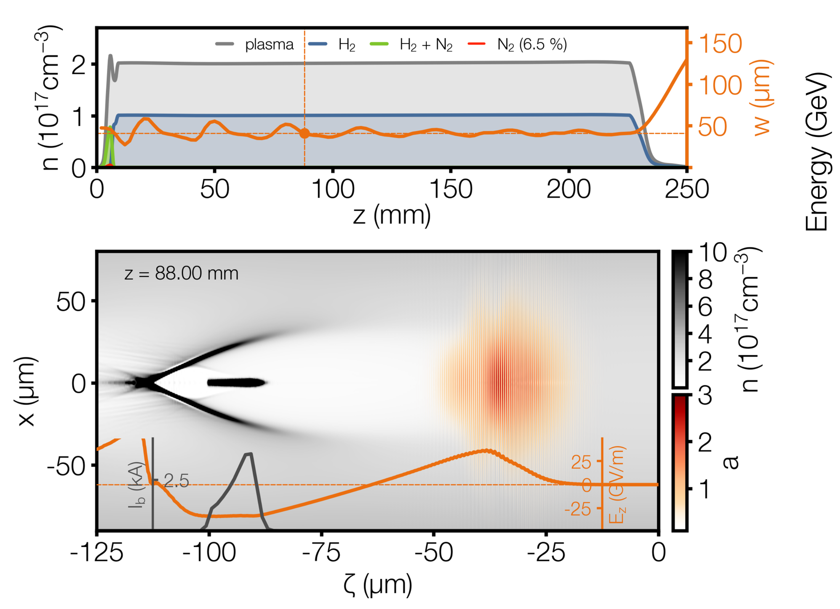
Optimization, jitter modeling, start-to-end

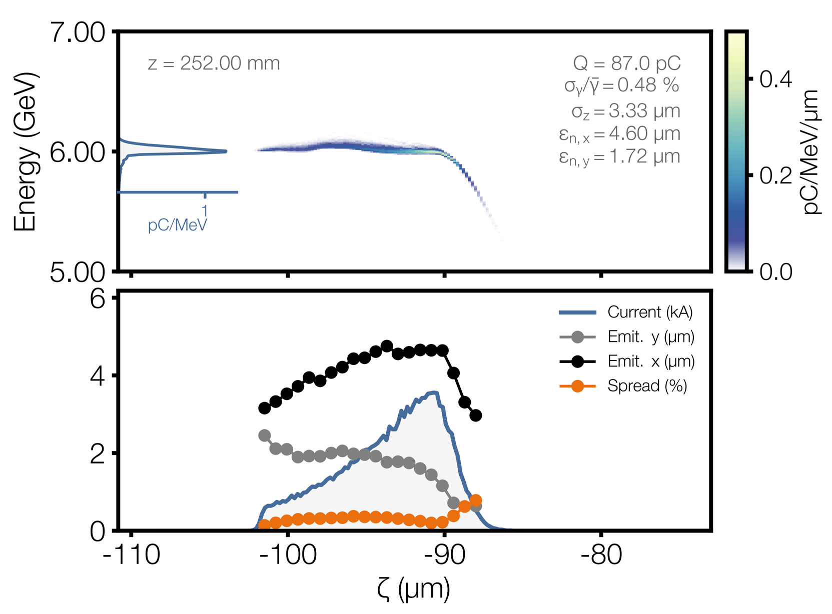
LPA optimization: FBPIC[6] and Optimas[7]

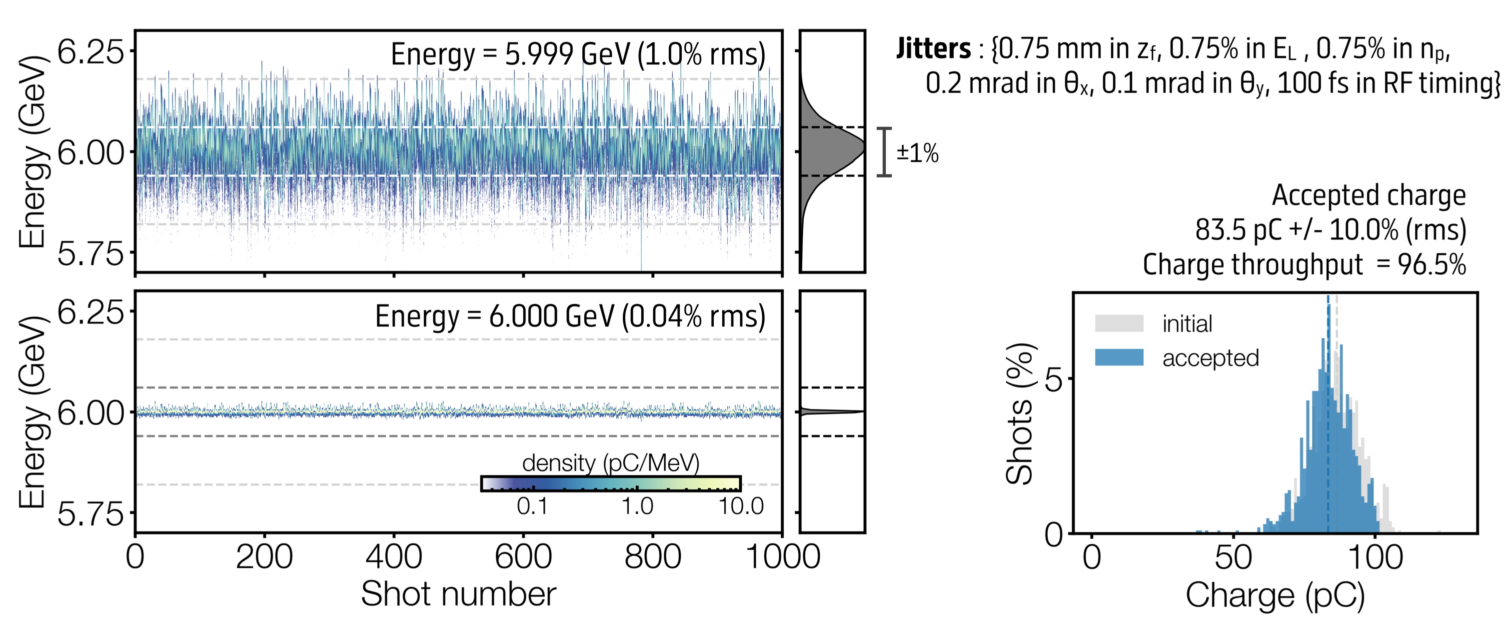
Maximizes the beam spectral density at 6 GeV
Minimizes the laser energy.

Start-to-end simulations: full jitter analysis, aided by surrogate modeling

Beamline simulations with OCELOT (tracking, collimation, CSR, RF, etc.)
Tracking in the storage ring with ELEGANT (wakefields, synchrotron radiation, etc.)







Laser pulse (flattened Gaussian)
$a_0 = 2.0$, $w_0 = 50$ μm, $P_0 = 345$ TW,
τ = 53 fs (fwhm), Energy = 19.6 J.

Plasma target
LUX-type profile: $n_p = 2 \times 10^{17}$ cm^{-3}
HOFI channel: $w_m = 50$ μm.

Electron beam
Charge: 87 pC, Energy spread: 0.5 %.
Emittance (norm): 4.6 μm, 1.7 μm.
Divergence: 0.2 mrad, 0.1 mrad.
Laser-to-beam energy efficiency: 2.7 %

Overall energy deviations reduced by a factor of 25 ➟ 0.04%
Emittance is preserved in the horizontal plane (chromatic correction).
Charge throughput 96%. No additional particle loss in the ring.

Operating PETRA IV

Repetition rate

- Filling the ring in 10 min.: 2.6 nC/s ➟ 80 pC @ 32 Hz.
- Top-up 1% of the charge every 6 min: 40 pC/s ➟ 80 pC @ 0.5 Hz.

Power consumption

- Realistic PIC simulations exhibit 2.7% laser-to-beam energy efficiency.
- The ECB enables 96% charge injection throughput.
- Modern diode-pumped laser systems perform with 1% wall-plug efficiency.

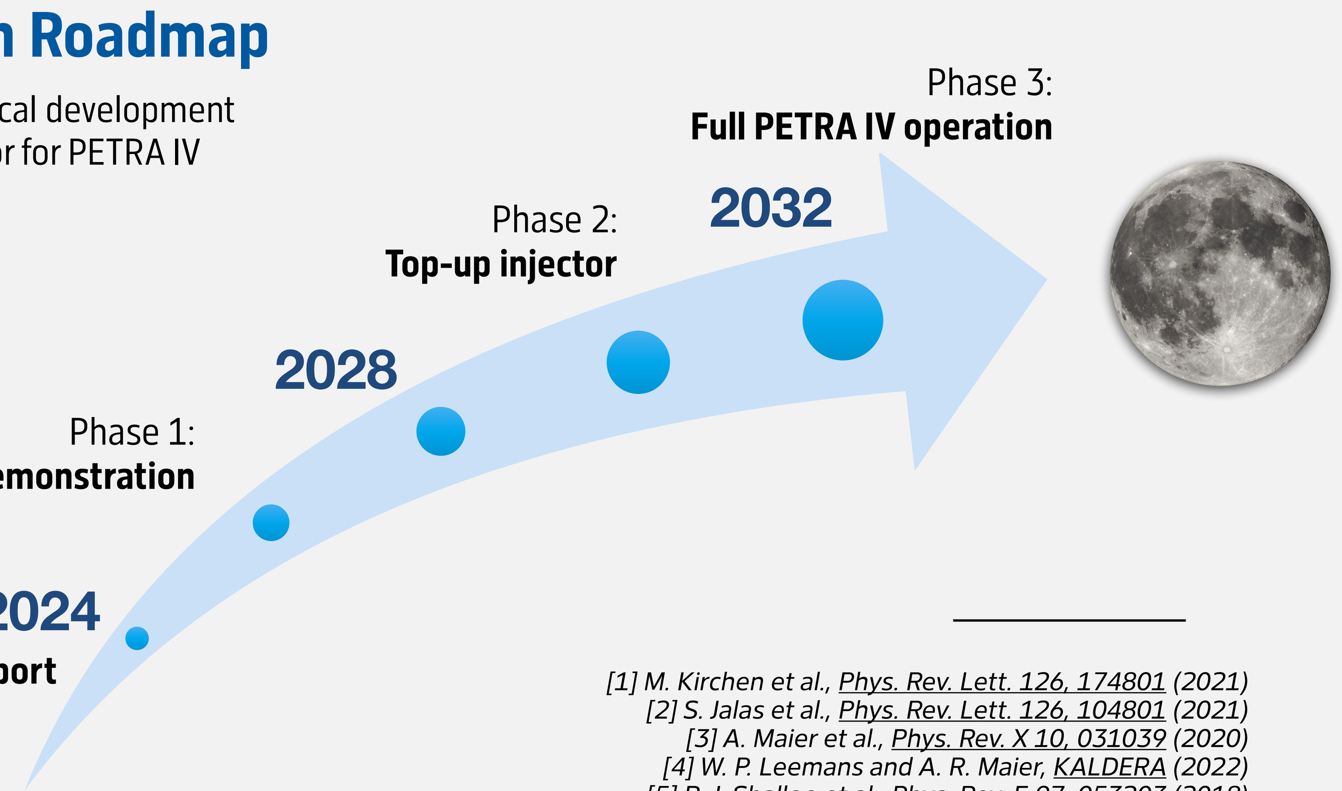
Average beam power
2.6 nC/s × 6 GeV = 15.6 W ⇨ Average laser (electrical) power
15.6 W / 0.026% = 60 kW
(0.026%: electrical-to-beam energy efficiency)

Average power consumption

Component	Power
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

Implementation Roadmap

DESY engages in the technical development phase of the plasma injector for PETRA IV



[1] M. Kirchen et al., Phys. Rev. Lett. 126, 174801 (2021)
[2] S. Jalas et al., Phys. Rev. Lett. 126, 104801 (2021)
[3] A. Maier et al., Phys. Rev. X 10, 031039 (2020)
[4] W. P. Leemans and A. R. Maier, KALDERA (2022)
[5] R. J. Shalloo et al., Phys. Rev. E 97, 053203 (2018)
[6] R. Lehe et al., Comp. Phys. Comm. 203, 66 (2016)
[7] A. Ferran Pousa et al., Phys. Rev. Accel. Beams 26, 084601 (2023)
[8] A. Ferran Pousa et al., Phys. Rev. Lett. 129, 094801 (2022)
[9] S. A. Antipov et al., Phys. Rev. Accel. Beams 24, 111301 (2021)

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