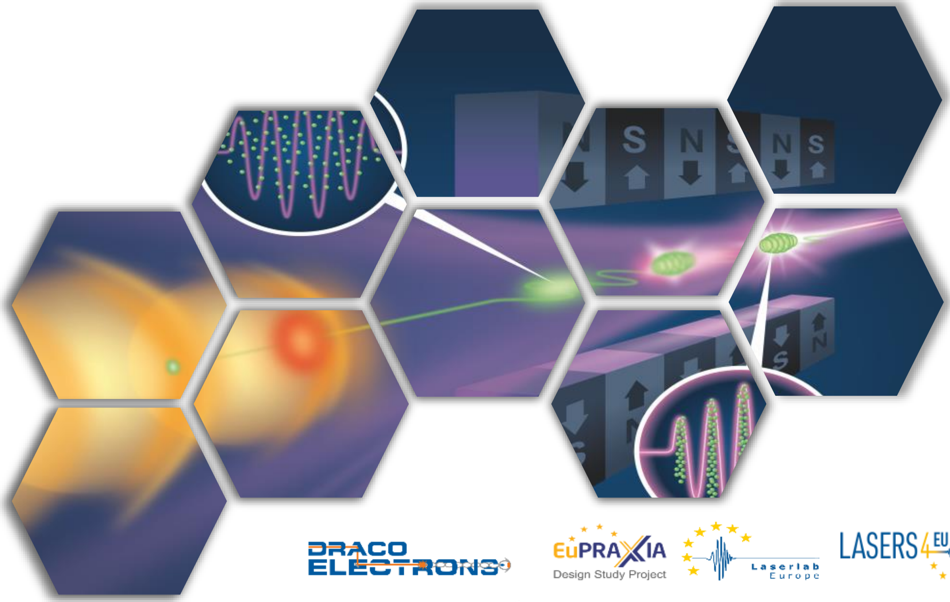
HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

SOLEIL SYNCHROTRON

PhLAM Physique des Lasers Atomes et Molécules

Recent progress in the LWFA-driven COXINEL FEL and its prospect towards shorter wavelengths lasing



Arie Irman *on behalf of COXINEL collaboration*
Helmholtz-Zentrum Dresden-Rossendorf

DRACO ELECTRONS

EuPRAXIA Design Study Project

Laserlab Europe

LASERS4EU

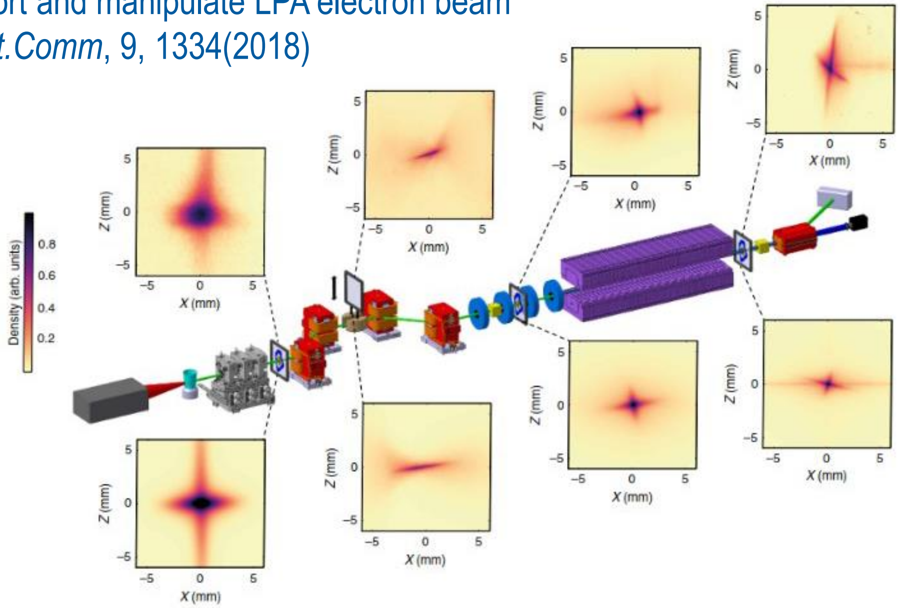
HZDR

COXINEL

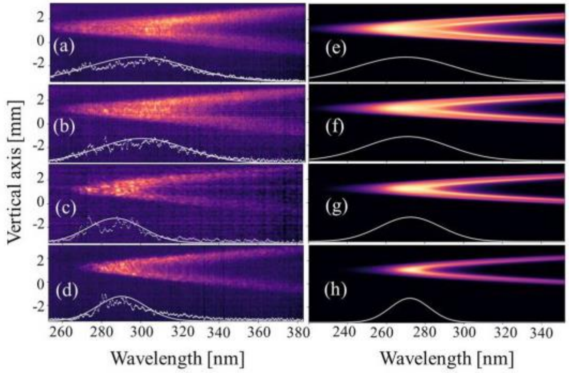
COherent X-ray source INferred from Electrons accelerated by Laser

- Demonstration **FEL** amplification in the **UV/VUV** range
- Seeded configuration : temporal **coherence**, control over **radiation wavelength**
- Initially installed at LOA (2016-2021) → transported to **HZDR Oct‘ 2021**

Control, transport and manipulate LPA electron beam
André et al, *Nat.Comm*, 9, 1334(2018)



Observation undulator radiation
Ghaith et al, *Sci.Rep*, 9, 19020(2019)

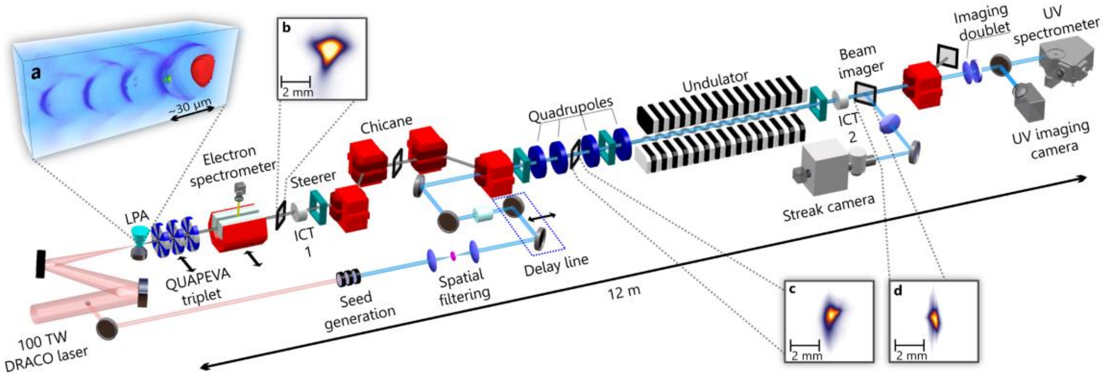


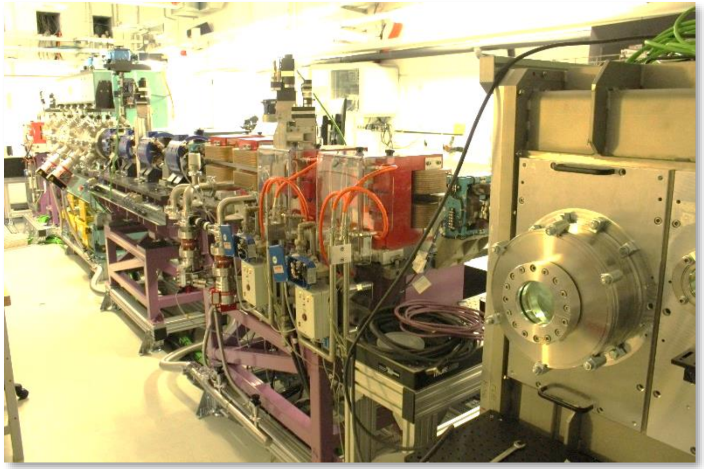
COXINEL@HZDR

- **Initial experiments (2022-2023) → low gain regime**
  - First lasing 275 nm, Tunability demonstration, Longitudinal coherence, Spatio-spectral profile
    Labat et al, Nat. Photonics 17, 150(2022), Labat et al, PRAB 28, 020702(2025), Labat et al, PRR 7, 023061(2025)

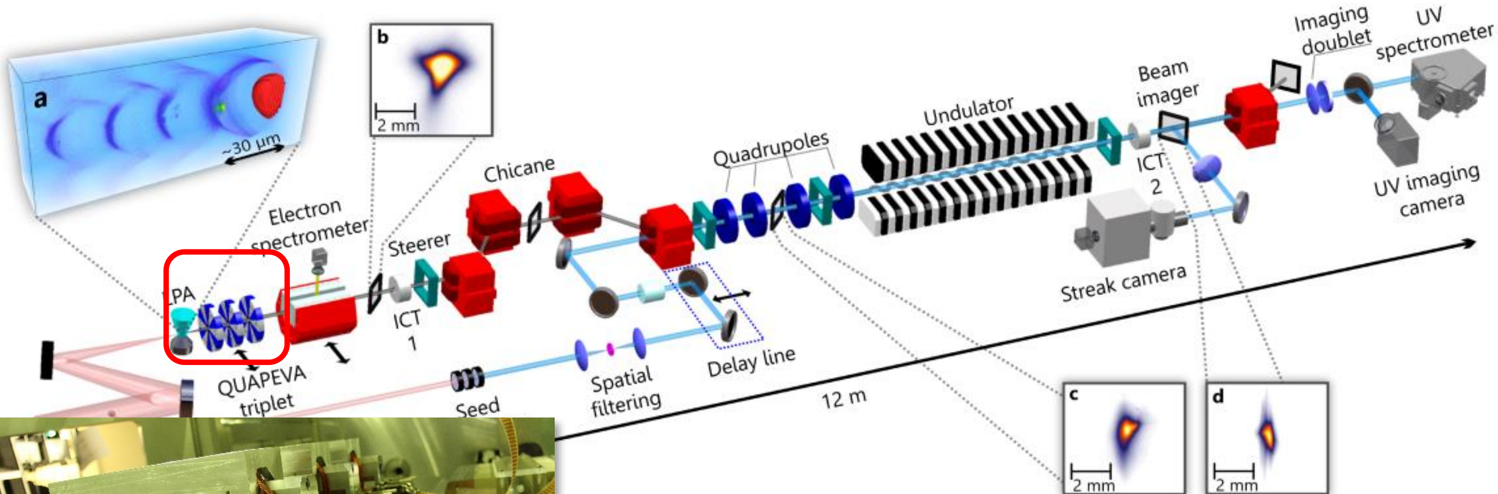
- **Recent experiments (2024) → exponential regime**
  - Stable LPA operation in the high-charge regime, tailoring seed laser intensity

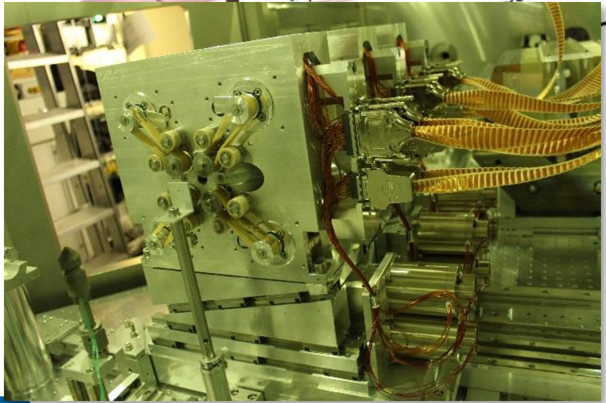
- **Outlook towards shorter wavelengths**





COXINEL@HZDR: Commissioning



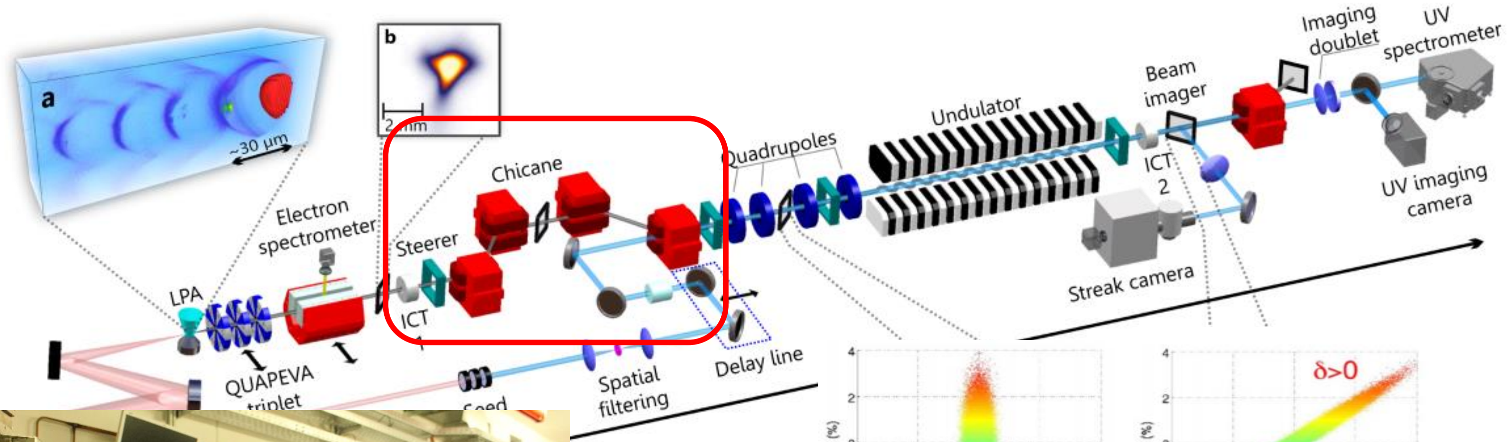


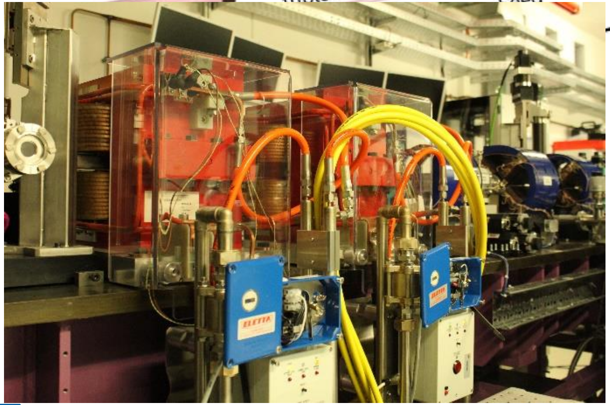
QUAPEVA Triplet

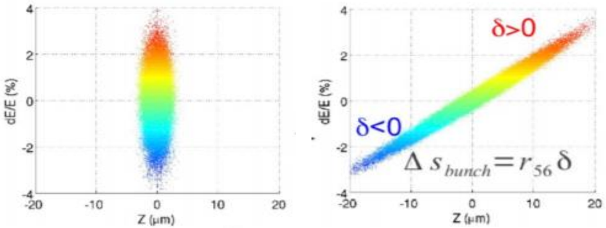
- permanent magnet variable quadrupoles
- immediate capturing, prevent emittance growth
- high gradient (up to 200 T/m)

F. Mathew et al, APL 111, 253503(2017), A. Ghaith et al, NIM A 909, 290(2018)

COXINEL@HZDR: Commissioning



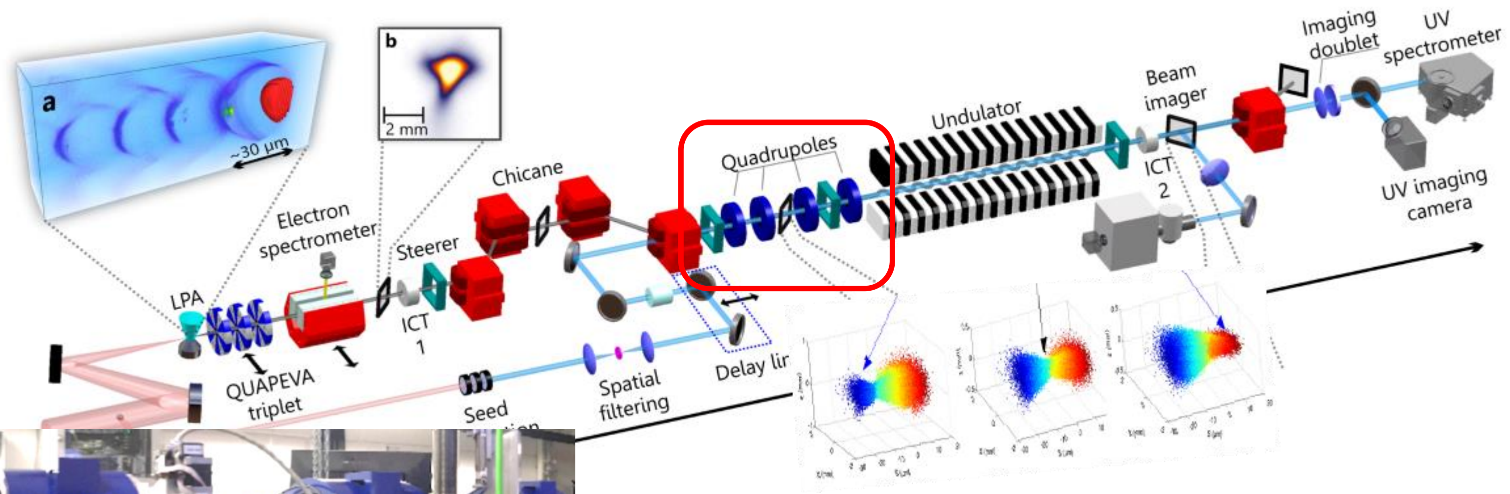


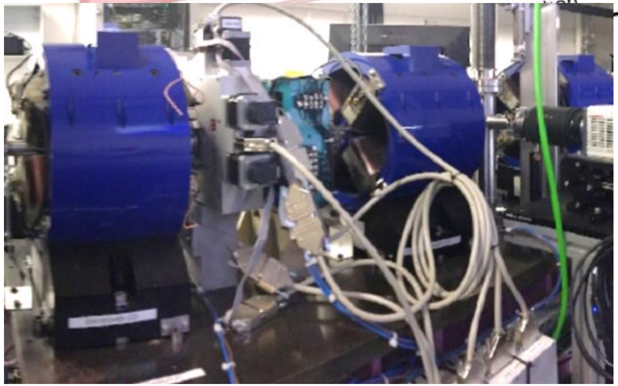


Chicane - decompression

- Reduce slice energy spread at cost of peak current

COXINEL@HZDR: Commissioning



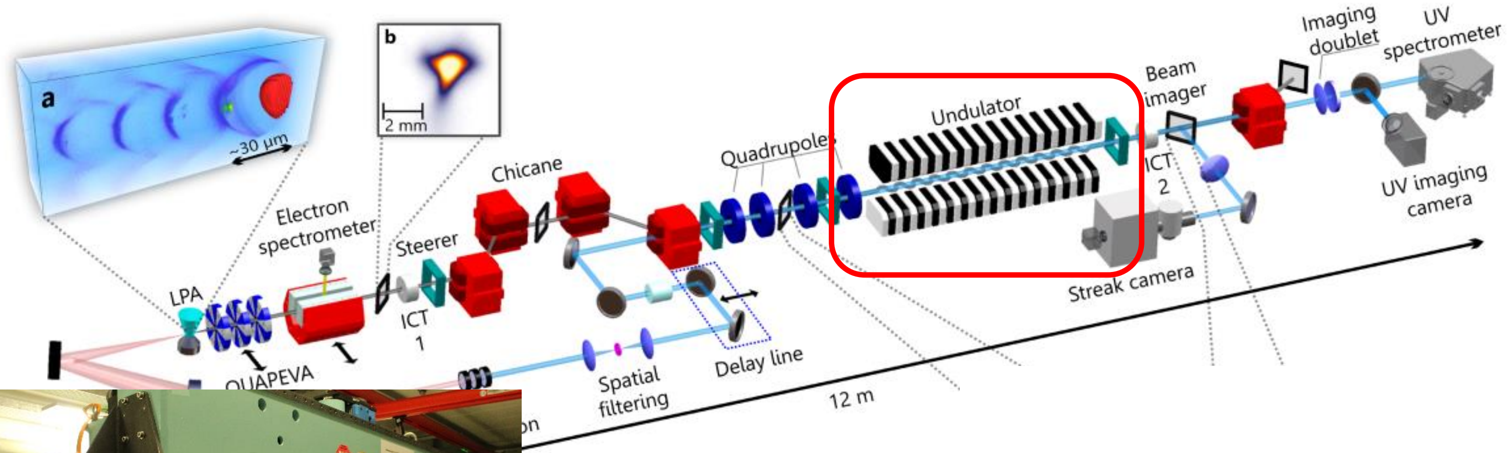


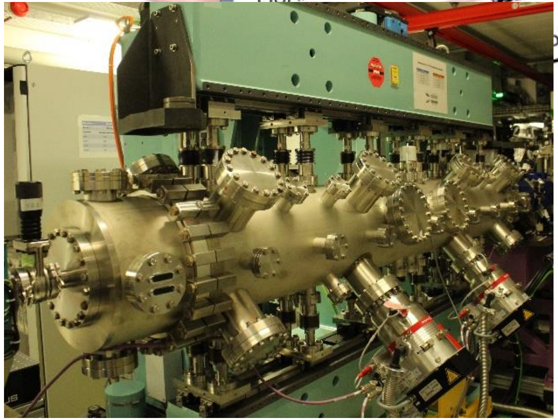
Electromagnetic Quadrupoles

- Chromatic matching along the undulator
  - maintaining minimum beam size synchronized to the radiation slippage → important for gain

A. Loulergue at al, NJP 17, 023028(2015)

COXINEL@HZDR: Commissioning

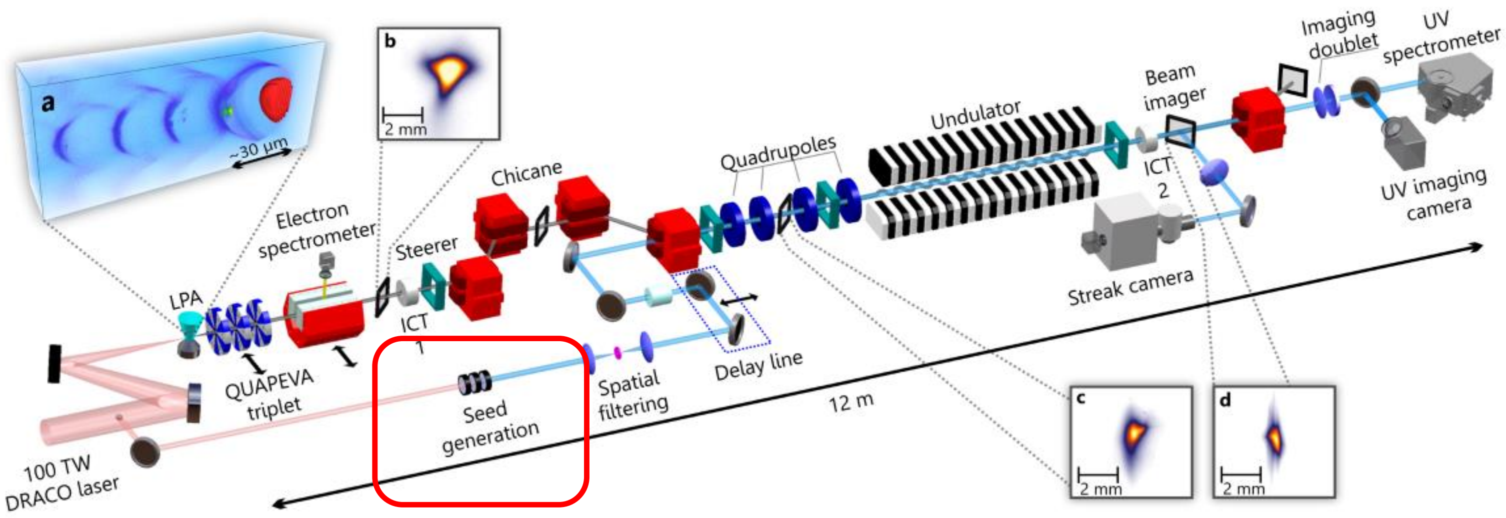




Undulator:

- In vacuum, λ_u=20mm, N_u=97, gap > 4mm, K_u<2.47
- Tapered geometry is possible

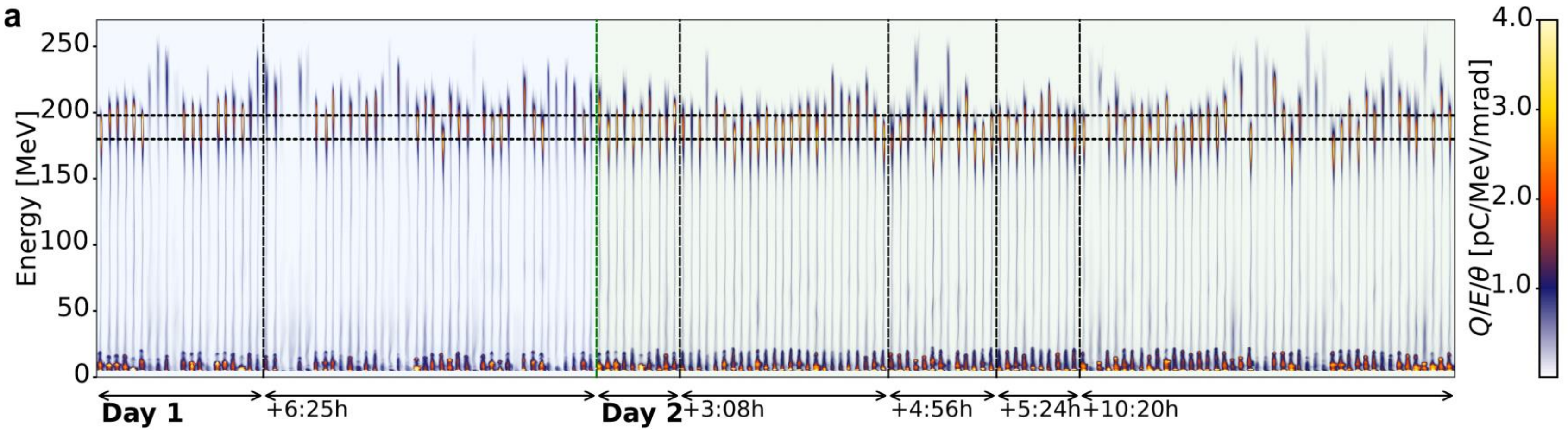
COXINEL@HZDR: Commissioning



Seed beam

- small fraction of the LWFA-laser driver – inherently synchronized
- frequency tripling to 269 nm
- temporally stretched to 1 ps

INITIAL EXPERIMENTS: Stable Multi-day LPA operation



Typical daily routine:

- Peak Energy : 188 MeV at 6 MeV s.d jitter
- Rel. Energy spread : 6.3% rms at 0.8% s.d jitter
- Spectral charge density: 6 pC/MeV at 1.3 pC/MeV s.d jitter

Full power focus optimization on target

8:00 | 10:00 | 11:00 | 13:00 | 18:00 | 24:00

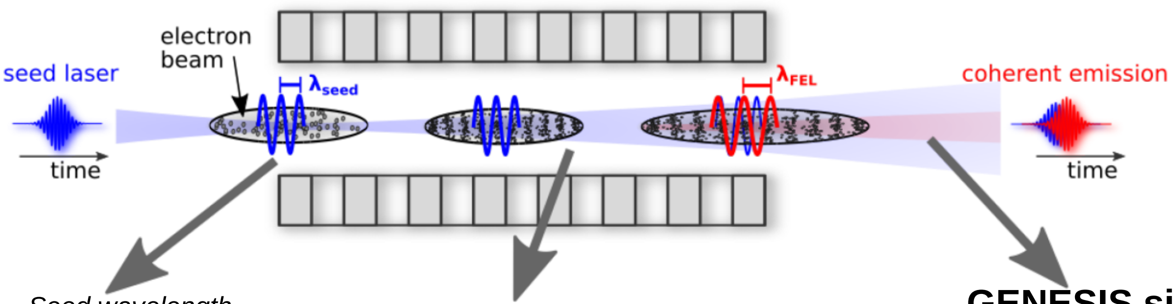
Laser start up and laser diagnostics

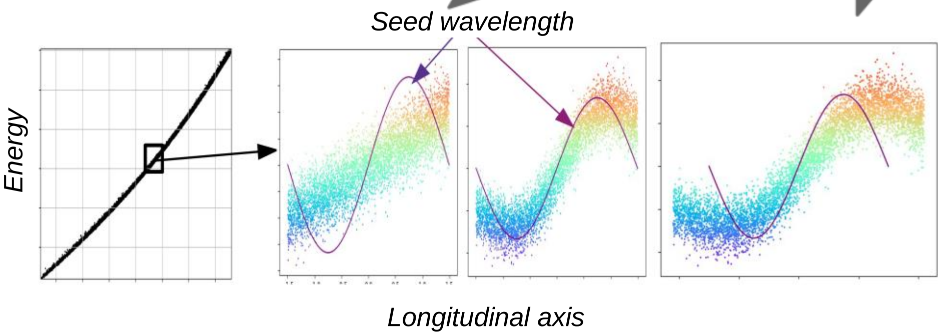
LWFA Performance optimization, beam transport through the beamline

Measurement:
Can go up to 10000 shots per-day

RED SHIFTED FEL W.R.T SEED

*A new **FEL regime** induced by the **chirp** (energy-time correlation) on the electron beam*

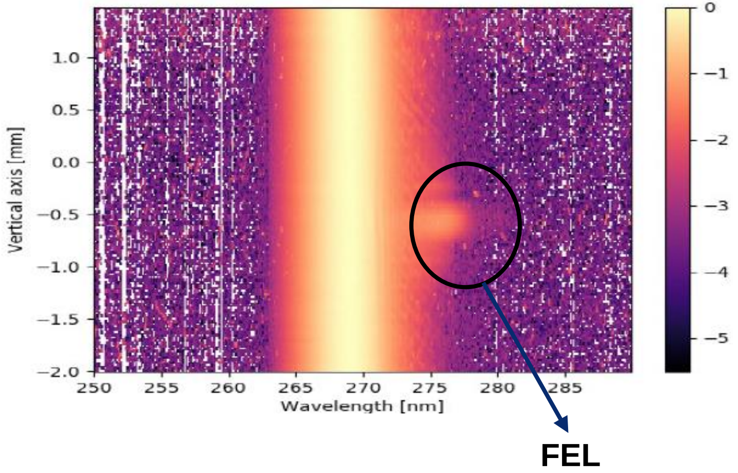




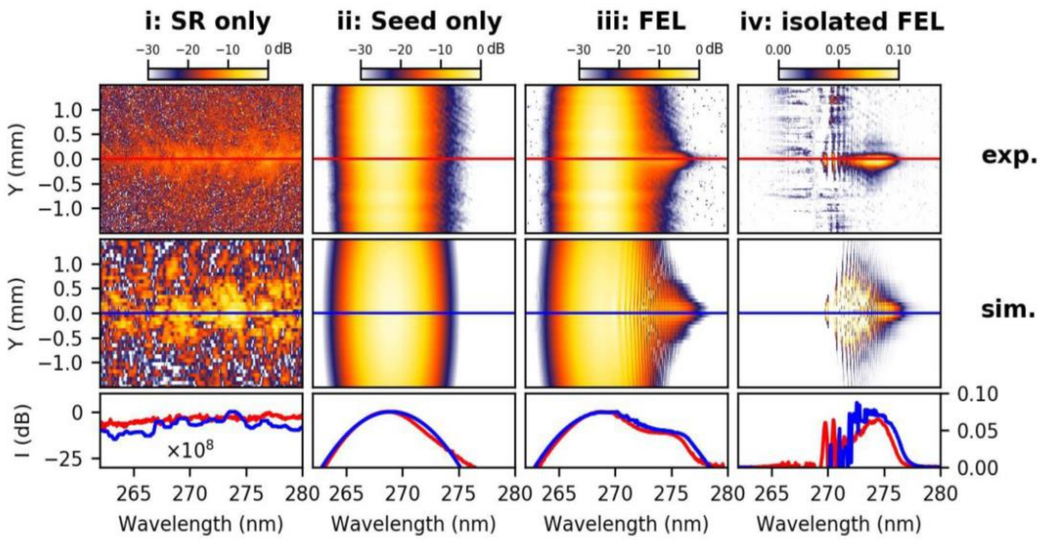
$$\lambda_{FEL} = \left(\lambda_0 + \frac{t_0 - \tau}{D_\lambda}\right) \times \left(1 + \frac{1 + K_{u0}^2/2}{\gamma(t_0)^2 R_{56}} L_{eff}\right)$$

M. Labat et al, NJP 22, 013051(2020)

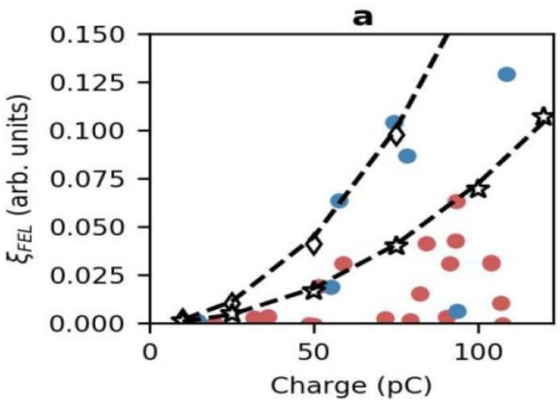
GENESIS simulation



INITIAL EXPERIMENTS: First lasing ~ 275 nm

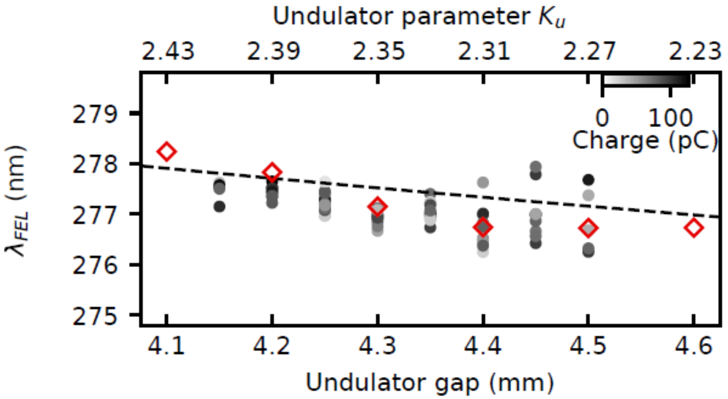


FEL quadratic charge dependence



INITIAL EXPERIMENTS: Demonstration of spectral control

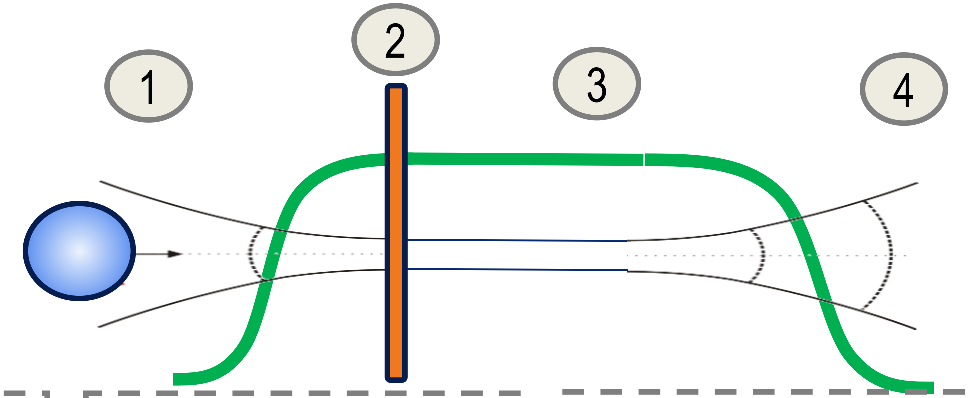
Undulator gap scan



M. Labat et al, PRAB, 28, 020702(2025)

(•) measurement (◊) Genesis

HIGH QUALITY ELECTRON BEAM → CONTROL OVER THE WHOLE PROCESS



1) Optimizing driver coupling into plasma
- Driver-transverse mode matching to plasma up-ramp profile
- Spectral-phase laser profile: GVD and TOD

2) Localizing electron injection
- Ionization injection (STII, plasma photocathode)
- Shock-front (hydrodynamic shock, optically field-ionization)

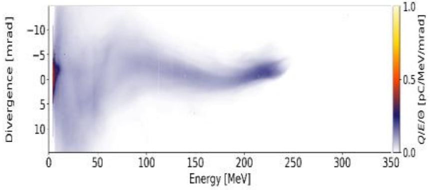
3) Stabilizing plasma wave propagation
- Laser guiding with less mode oscillation
- Minimizing driver deceleration
- Flattened plasma density profile
- Beam phase-space manipulation

4) Beam extraction
- Adiabatic matching
- Tailoring plasma density downramp

SPATIO-TEMPORAL LASER CONTROL

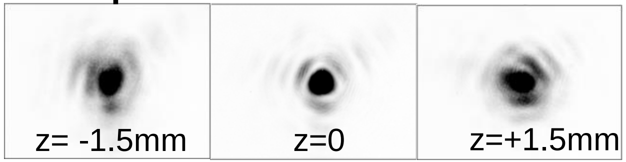
→ key for better laser-plasma coupling efficiency and stability

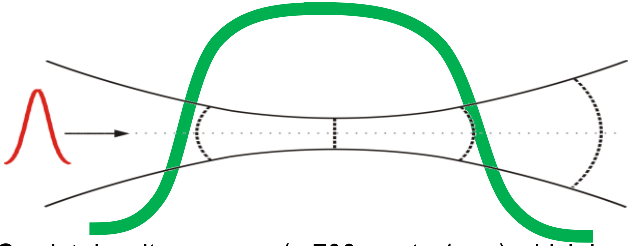
PFT error: bad e-beam

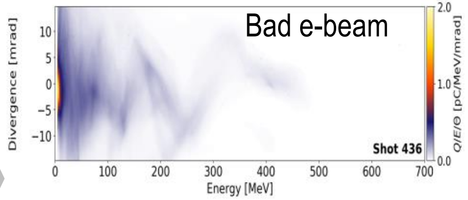


multiple plasma waves

Not optimized Laser transverse mode



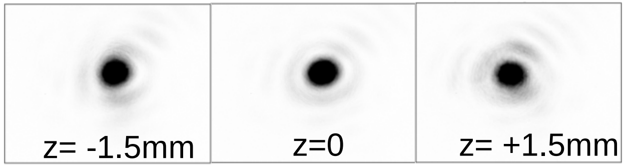


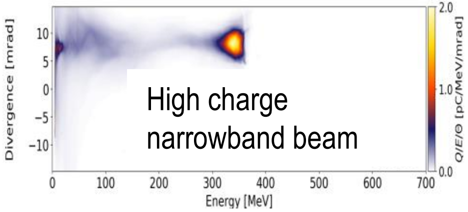


Gas jet density up-ramp (~ 700 μm to 1mm) which is comparable with the laser Rayleigh lenght

→ ***Laser-plasma interaction*** *starts at* ***the mid-field***

Good Laser transverse mode





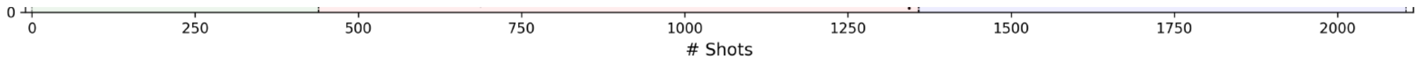
RECENT EXPERIMENTS

- **Better LPA beam parameters**: higher charge (**350 pC-fwhm**), spectral charge density **~10 pC/MeV –** STII regime powered by 150 TW Draco laser

05.12.2024 …….. *11.12.2024* Consistent beams for 2 weeks

- **Better beam stability (energy, charge, pointing):** allowing **precise transport** and **alignment** through the undulator

Blue ⟶ entrance of the beamline
Black ⟶ end of the beamline



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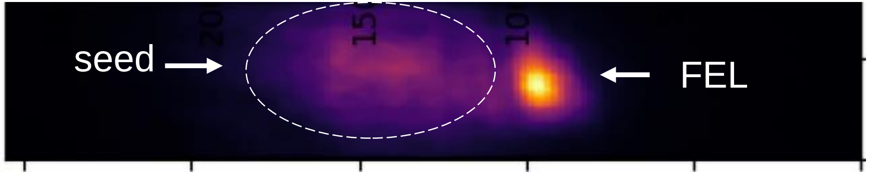
RECENT EXPERIMENTS

- Increasing **the seed intensity by reducing pulse duration** → microbunching occurs faster, higher FEL output for a fixed undulator length, **gain length < undulator length**

- Seed energy ~ 250 nJ, FEL signal up to **45 nJ/pulse**
  Note! Only a small fraction of this seed responsible in the FEL process



at 0th order of spectrometer

Output power vs undulator length
(Genesis Sim: Gain length ~ 55 cm)

Energy measurement

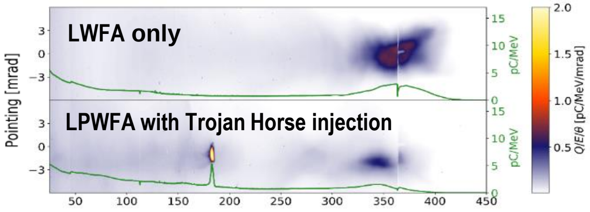
Up to 45 nJ

$$\hat{P}_{\mathrm{FEL}} \propto e^{z/L_g}$$

TOWARDS SHORTER WAVELENGTHS

- Deploying PW-arm of the DRACO laser and exploiting injection schemes:

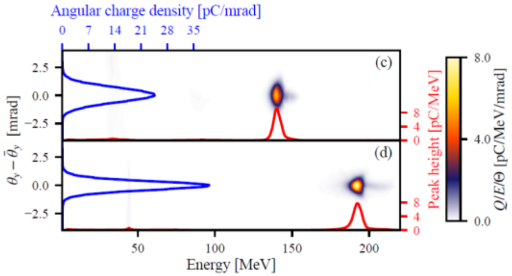
Plasma Photocathode in hybrid LPWFA platform



Witness parameters:
10 pC charge**, 0.6 mrad divergence, 0.7% rel. energy spread**

Schöbel et al Invited talk Wed. 10:00

Ionization assisted downramp in a gas cell



Fixed C1 pressure:
C2: 20 mbar → C2: 35 mbar,
E_p: 140 MeV → 193 MeV
ΔE: 5.6 MeV → 6.5 MeV
Div: **0.67 mrad → 0.46mrad**
Charge is preserved (70 pC)

Lodewyk et al Invited talk Tue. 11:30

- Upgrade the undulator: cryo-cooled permanent magnet CPMU 15 mm

TOWARDS SHORTER WAVELENGTHS

Design parameter using STII beams

IMPLEMENTATION AND COMMISSIONING PLAN (2026-2029)

111b

THANK YOU FOR YOUR ATTENTION !

Many thanks to:

HZDR team:

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COXINEL collaboration:

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Eléonore Roussel

Sébastien Corde
Olena Kononenko and team

Diagnostic collaboration:

Victor Malka

Michael Downer

Alex Lumpkin

Hybrid collaboration:

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Ralph Assmann

Sébastien Corde
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and team

Stefan Karsch
Andreas Döpp and team

Bernhard Hidding and team