Recent progress on the COXINEL seeded FEL based on laser-plasma acceleration

M. Labat, on behalf of A. Berlioux, P. Berteaud, F. Blache, S. Bock, F. Bouvet, F. Briquez, Y.Y. Chang, S. Corde, J. Couperus, M.E. Couprie, A. Debus, C. De Oliveira, J.P. Duval, Y. Dietrich, M. El Ajjouri, C. Eisenmann, J. Gautier, R. Gebhardt, A. Ghaith, S. Grams, U. Helbig, C. Herbeaux, N. Hubert, A. Irman, C. Kitegi, O. Kononenko, M. Kuntzsch, M. LaBerge, S. Lé, B. Leluan, A. Loulergue, V. Malka, F. Marteau, M.H. N Guyen, D. Oumbarek-Espinos, R. Pausch, D. Pereira, R. Prazeres, T. Püschel, J.P. Ricaud, P. Rommeluere, E. Roussel, P. Rousseau, S. Schöbel, M. Sebdaoui, U. Schramm, K. Steiniger, K. Tavakoli, C. Thaury, P. Ufer, M. Valléau, M. Vandenberghe, J. Vétéran.

24–26 September 2025, FELs of Europe topical workshop, Grado (Italy)

RFA based FELs developments

- FELs developed based on Radio–Frequency Accelerators (RFA)

  → taking advantage of fast developments for the high–energy physics accelerators

- Last few decades developments:

  → Temporal coherence, short pulse duration, multi-color pulses, variable polarization, etc..

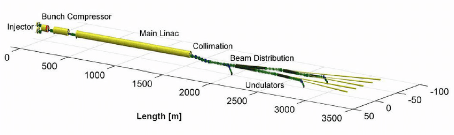
- More recent topics:

  → High intensity THz generation, high repetition rate (MHz) operation, energy-consumption saving, compactness, etc..

  (*this workshop*)

FEL compactness ?

- RF acceleration limited to < 100 MV/m gradient
- To produce few GeV beams for sub–nm lasing
  $\rightarrow$ linacs are several hundreds of meters long
  (750 m for 5 GeV, 1.4 km for 14 GeV)



European X-ray FEL (0.05–0.15 nm) layout from Zapfe, J. Phys.: Conf. Ser. 100, 092001 (2008).

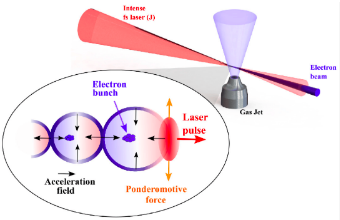
$\rightarrow$ Why not using Laser Plasma Acceleration ?

Towards LPA based FELs... (1979 – 2022)

1979: LPA concept [1]

[1] Tajima & Dawson, Laser electron accelerator, Phys. Rev. Lett. 43, 267 (1979)

- Ultra-short and relativistic intensity laser pulses focussed into a gas
- Generation of a plasma housing micron size accelerating structures with high accelerating gradients (>100 GV/m)



Plasma accelerator sketch. Figure from Kim, Appl. Sci. 11 (2021).

2004: LPA first demonstrations

- With the advent of laser Chirped Pulse Amplification [1]...
- ... First quasi–monochromatic beams ($\sigma_e < 10\%$) produced [2]

[1] Strickland & Mourou (1985).

[2] Faure et al., Nature 431 (2004), Geddes et al., Nature 431 (2004), Mangles et al., Nature 431 (2004).

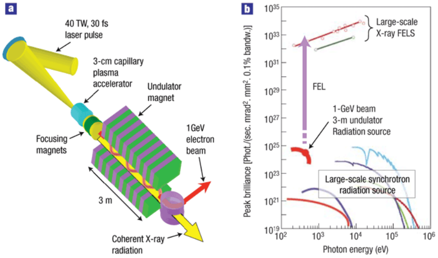
2007–2008: First LPA based FEL proposals

- *Design considerations for table-top, laser-based VUV and X-ray FELs*

  F. Grüner et al., Applied Physics B 86, 431–435 (2007).

- *Towards a table-top free-electron laser*

  K. Nakajima, Nat. Phys. 4, 92–93 (2008).



2010's: Early LPA experiments...

Several attempts to get an LPA based FEL (2008–2020):

Schlenvoigt et al, *Nat.Phys.* 4, 130(2008)

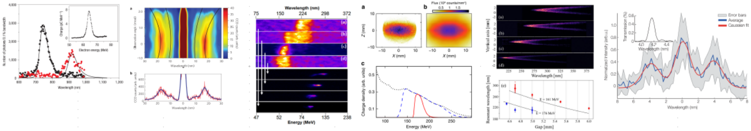
Fuchs et al, *Nat.Phys.* 5, 826(2009)

Anania et al, *APL*, 104, 264102(2014)

André et al, *Nat.Comm*, 9, 1334(2018)

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

Maier et al, *Sci.Rep*, 10, 5634(2020)



→ Only Synchrotron Radiation observed...

2010's: Why first attempts failed....

Radio–Frequency Accelerators:

- Charge: 10 pC up to 1 nC
- Divergence: $<$ mrad
- Slice emittance: $\approx 0.5\pi$.mm.mrad
- Chromatic emittance: small...
- Energy spread : < 0.1 %
- Energy : from few MeV up to few GeV
- Stability : $< 1\%$
- $\rightarrow$ Gain length < 1 m

Laser Plasma Accelerators:

- Charge : few 10's of pC
- Divergence : $>$ few mrad
- Slice emittance: $\approx 0.2\pi$.mm.mrad
- Chromatic emittance: large !!!
- Energy spread : ≈ 10 %
- Energy : from few MeV up to few GeV
- Stability : > 100 % ???
- $\rightarrow$ Gain length $>$ several meters...

$\rightarrow$ Divergence, emittance and energy spread were too high !!!

$\rightarrow$ No gain...

2010's: Which strategy then ? (To get an LPA based FEL in these conditions)

Several strategies:

1. Wait for LPA performance to improve
2. Couple an RF injector with a plasma accelerator
3. Try to find some tricks

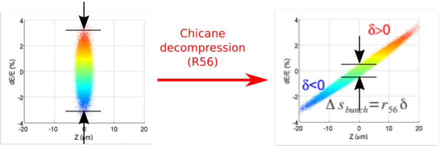
Strategy #3: find some tricks

Several tricks proposed:

- Horizontally disperse and couple the beam in a Transverse Gradient Undulator [1]
  → no experiment
- Decompress and couple the beam in a suitably tapered undulator [2-3]
  → no experiment
- Decompress and use a chromatic matching [4]
  → COXINEL

[1] Z. Huang et al., Phys. Rev. Lett. 109, 204801 (2012).
[2] A.R. Maier et al., Phys. Rev. X 2, 031019 (2012).
[2] T. Seggebrock et al., Phys. Rev. ST Accel. Beams 16, 070703 (2013).
[4] A. Loulergue et al., New J. Phys. 17, 023028 (2015).

Trick → decompression + chromatic matching (1)



Large slice energy spread — Small slice energy spread

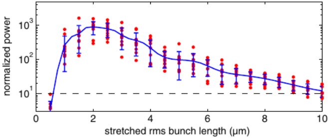


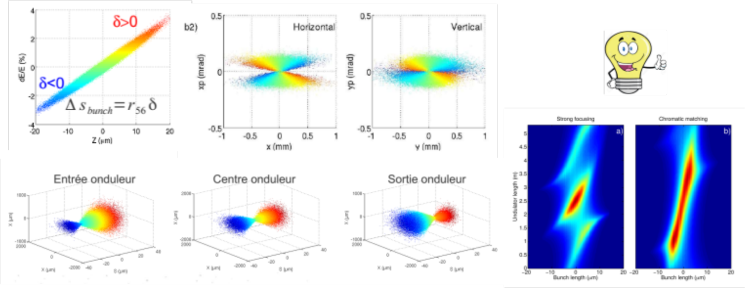
Fig.4 from [1].

- LPA beam at source: energy spread $\geq 1\%$ → no FEL
- After beam decompression in a chicane [1] → slice energy spread reduction
  (at cost of peak current)

→ Hudge gain increase

[1] A.R. Maier et al., Phys. Rev. X 2, 031019 (2012).

Trick → decompression + chromatic matching (2)



Chromatic matching [1]:

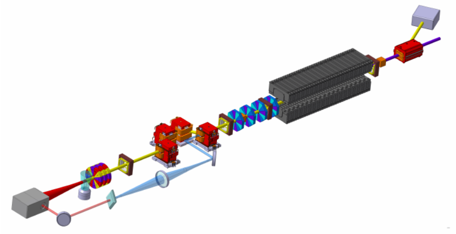
- Focuss particles according to their energy along undulator
- Synchronize focussing with slippage

→ Maximize gain along undulator → speed up FEL amplification

[1] A. Loulergue et al., New J. Phys. 17, 023028 (2015).

2013: COXINEL project [1]

COherent X-ray source INferred from Electrons accelerated by Laser / European Research Council for COXINEL Grant (340015)



Concept:

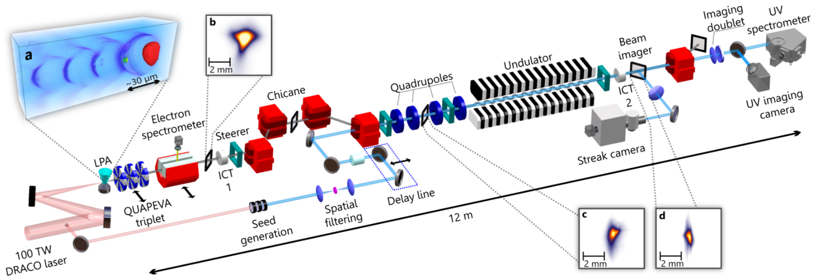
- LPA beam of LOA (180 MeV)
- Decompression + chromatic matching
- 1 single undulator
- A seeded configuration

Aim:

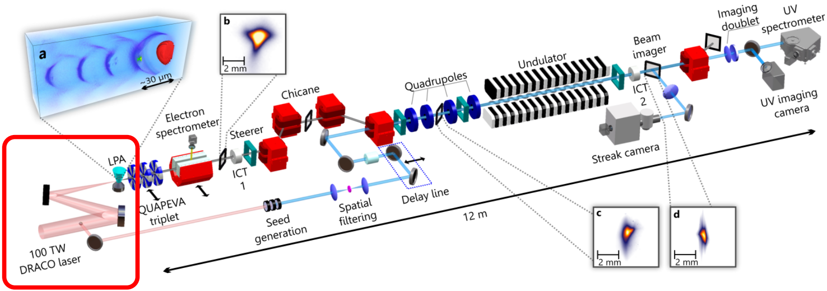
- LPA based FEL at 270 nm (as first step)
- LPA based FEL at 40 nm

[1] M.E. Couprie et al., J. Physics B : At., Mol. Opt. Phys. 47, 234001 (2014) / Plasma Phys. Control. Fusion 58, 034020 (2016).

Experimental setup



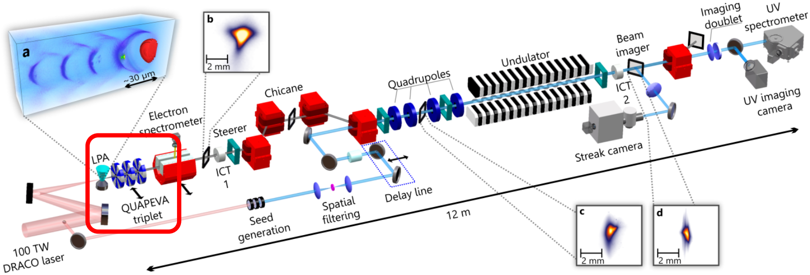
Experimental setup



Electron beam delivered by LOA Salle Jaune LPA:

- Energy: 175 MeV
- Energy spread: $\approx$20 %
- Divergence: 4—5 mrad–RMS
- Charge density: $<$ 1 pC/MeV

COXINEL beamline

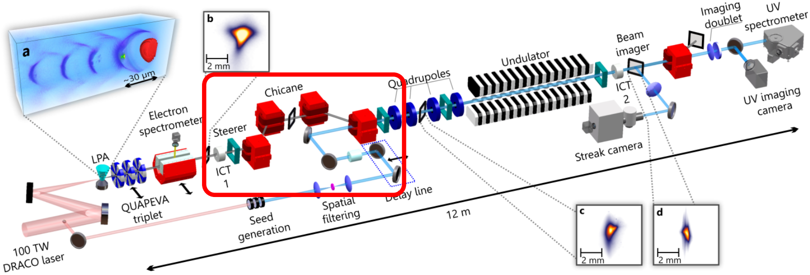


QUAPEVA triplet [1,2] = permanent magnet variable quadrupoles

- High gradient (up to 200 T/m) + Very compact (10 cm long)
- → Immediate refocussing to prevent emittance growth

[1] F. Marteau et al., Appl. Phys. Lett. 111, 253503 (2017). [2] A. Ghaith et al., NIM A 909, 290-293 (2018).

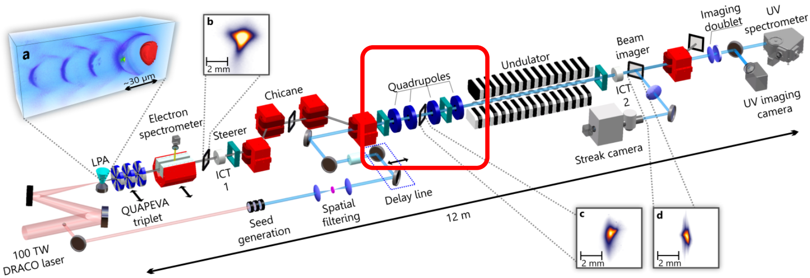
COXINEL beamline



Chicane = four electromagnetic dipoles

- → Chicane decompression
- → Energy sorting + Slice energy spread reduction (at peak current cost)

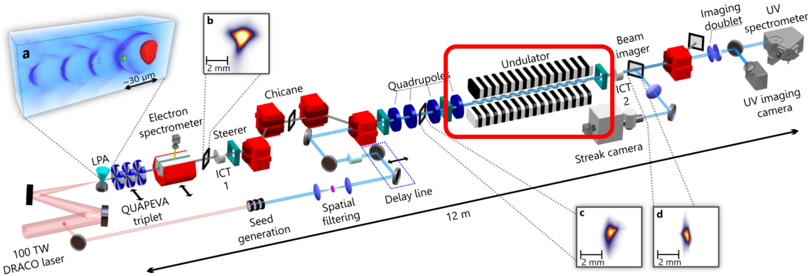
COXINEL beamline



Quadrupoles = four standard electromagnetic quadrupoles

- → Beam phase–space manipulation
- → Chromatic matching

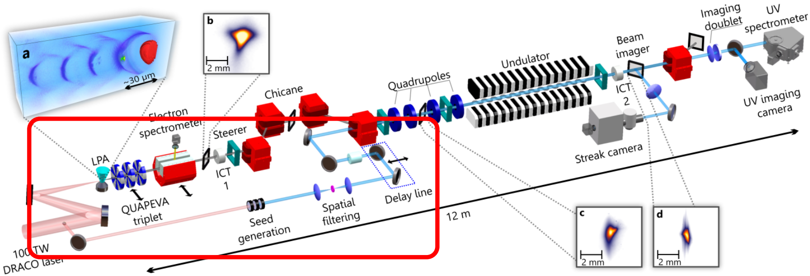
COXINEL beamline



Undulator:

- In–vacuum U20, λ_u=20 mm, N_u=100, gap>4 mm, K_u <2.47
- → SR emission
- → Gain housing

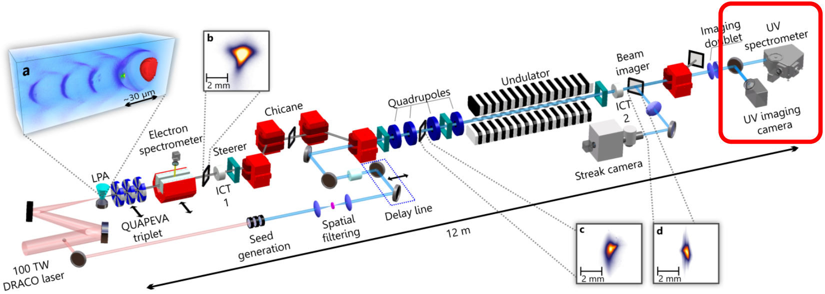
COXINEL beamline



Seed:

- Generated from main laser by frequency tripling in BBO-crystals $\longrightarrow$ 268 nm
- Spatial filtering
- Temporal shaping using FuSi rods

COXINEL beamline

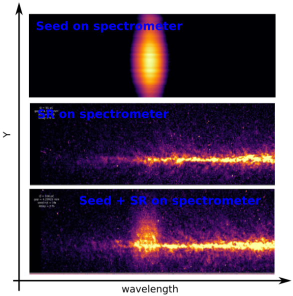


Output radiation diagnostics:

- 2D imaging spectrometer
- Radiation imaged on spectro. entrance slit with a near–field imaging system
- → Spatiospectral intensity distribution

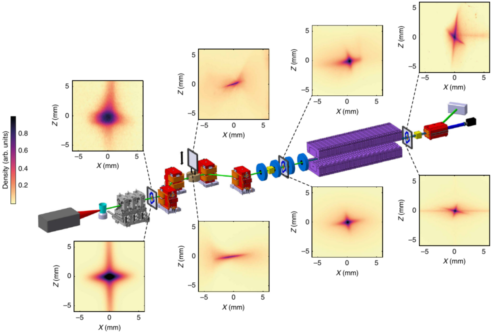
COXINEL beamline

Examples of spatiospectral intensity distributions:



2018: COXINEL first achievements @ LOA (France)

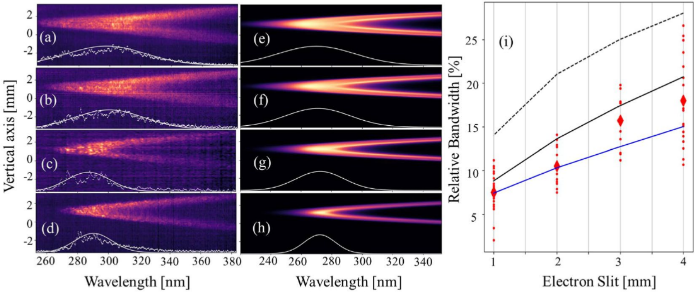
- First LPA beam controled transport [1] (using chicane decompression + chromatic matching)



[1] T. André et al., Nature 9, 1334 (2018).

2019: COXINEL first achievements @ LOA (France)

- First LPA based narrow–band SR emission [2]



[2] A. Ghaith et al., Scientific Reports 9, 19020 (2019).

2020: COXINEL beamline still not lasing

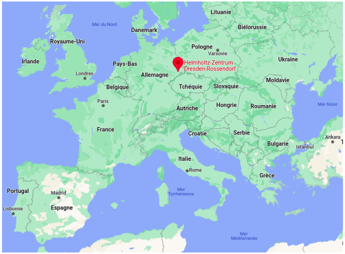
→ Indeed, still no FEL...

- Divergence was too high (expected $<$ 1 mrad / measured $>$ 2 mrad)
- Charge density was too low (expexted $>$ 10 pC/MeV / measured $<$ 1 pC/MeV)

2020: COXINEL beamline moves...

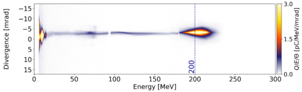
Sept. 2020: COXINEL beamline is moved to Helmholtz-Zentrum Dresden-Rossendorf (Germany)

which LPA seemed more suited for an FEL demonstration

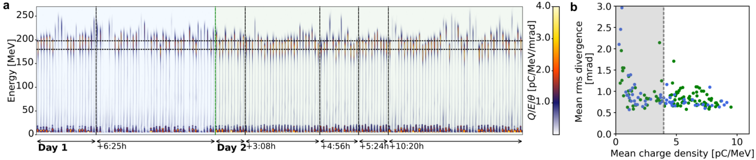


LPA beam properties @HZDR

- Charge density: 5–10 pC/MeV
- Divergence: < 1 mrad–rms
- Emittance: ≈ 1 mm.mrad
- Stability: >8 hours stable operation + day–to–day reproducible properties



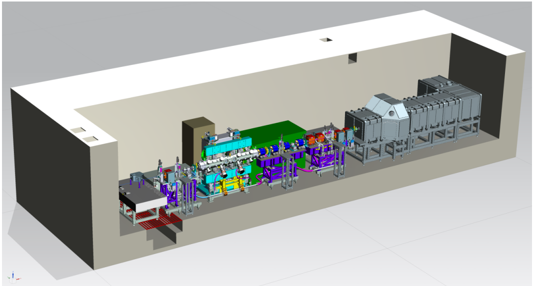
Single shot spectrometer acquisition.

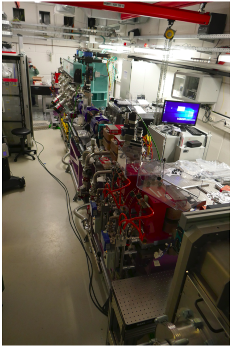


Electron beam records over two days of FEL experiment

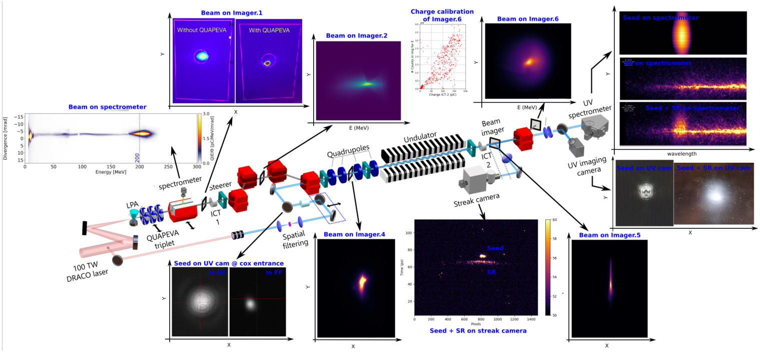
2021: COXINEL beamline has moved

Oct. 2021: COXINEL beamline is installed into 111c LPA cave





2021: Commissioning of COXINEL beamline (≈ 12 days)



→ Ready to start FEL experiments in January 2022...

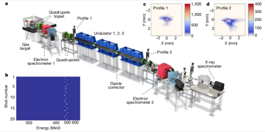
2021: Meanwhile...

...

2021: Meanwhile... First plasma based FEL signals

SIOM-CAS (China)

Wang, Nature 595, 516 (2021).

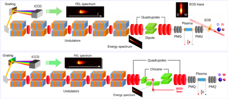


- LWFA beam
- SASE configuration
- High–gain regime
- Lasing @27 nm

SPARC_LAB (Italy)

Pompili, Nature 605, 659 (2022).

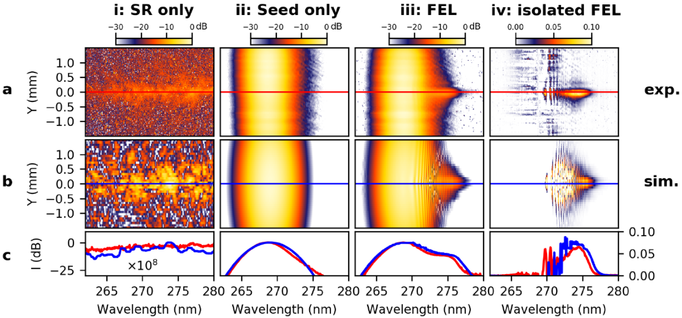
Galletti, PRL 129, 234801 (2022).



- RFA + PWFA beam
- SASE+seeded configuration
- High–gain regime
- Lasing @820 nm

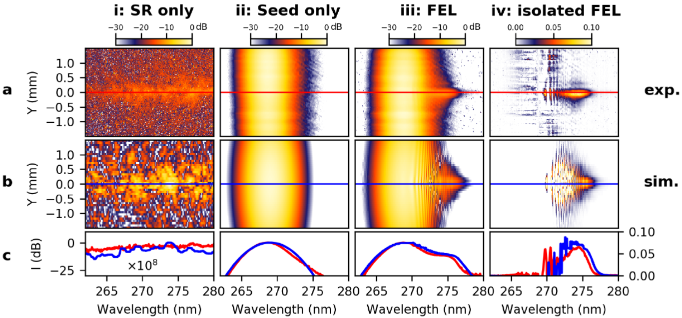
Results on COXINEL (2022–2025)

LPA based seeded FEL demonstration (2022)



* M. Labat et al., Nat. Photonics (2022).

LPA based seeded FEL demonstration (2022)



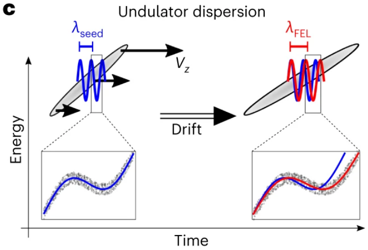
→ A peculiar FEL signal: red–shift + fringes

* M. Labat et al., Nat. Photonics (2022).

Red–shift and fringes

- Red–shift:

Strong beam chirp → stretching of modulation wavelength

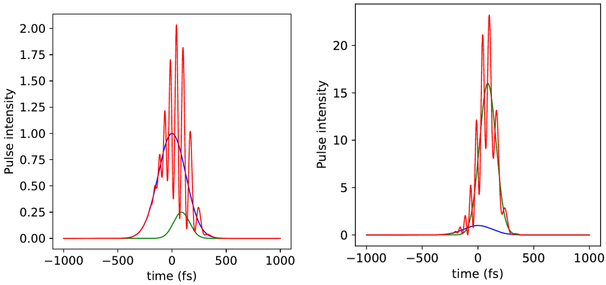


$$\lambda_{FEL} = \lambda_{seed} + \frac{\lambda_{seed} L_{eff}}{\gamma_0^2 R_{56}} (1 + K_u^2/2)$$

Red–shift and fringes

- Fringes:

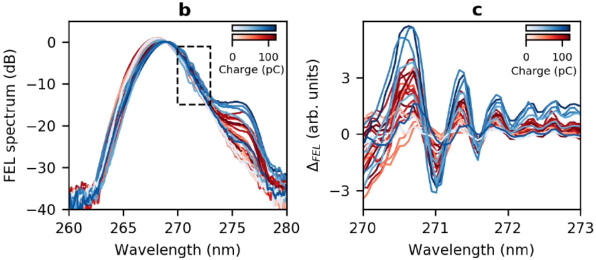
  Seed and FEL are 2 coherent pulses at $\neq \lambda \rightarrow$ interference fringes



(Blue) A_{seed}, (Green) A_{CE}, (Red) A_{FEL}.

LPA based seeded FEL demonstration (2022)

Observation of phase–locked fringes / interferences:



Experimental measurements recorded after optimization (blue) and one hour later (red).

→ demonstration of the temporal coherence of our LPA based seeded FEL

(no temporal coherence at SIOM in SASE)

* M. Labat et al., Nat. Photonics (2022).

FEL tunability and its modeling (2023)

- FEL standard tunability: (γ, K_u but seed has to be adjusted....)

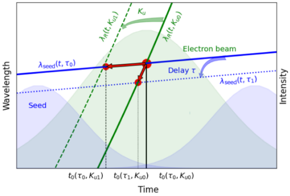
$$\lambda_{FEL} = \lambda_R = \lambda_{seed} = \frac{\lambda_u}{2\gamma^2} \times \left(1 + K_u^2/2\right)$$

- Red–shifted initial (2022) tunability: (R_{56}, τ and D_λ, with same seed)

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

- Red–shifted refined (2023) tunability: (R_{56}, τ and D_λ and K_u, with same seed)

(skipping maths for your safety but see M. Labat et al., Phys. Rev. Accel. Beams 28, 020702 (2025) for details)

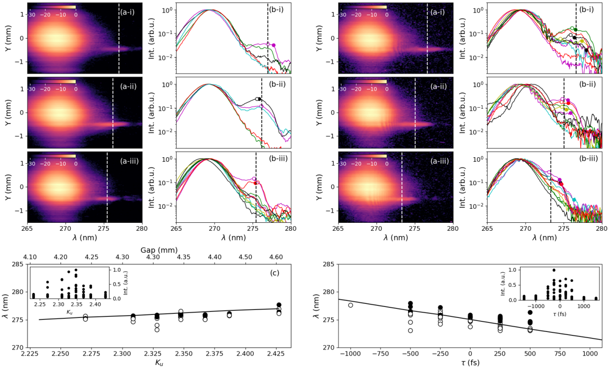


FEL tunability and its modeling (2023)

- With an improved beam quality...

  (still 5 % energy spread, 1.5 mrad divergence but 5 pC/MeV)

- Demonstration of our FEL tunability vs τ and K_u

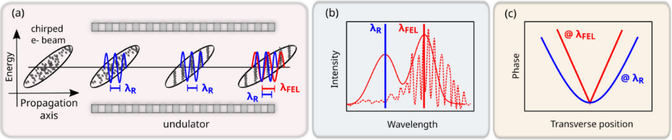


M. Labat et al., Phys. Rev. Accel. Beams 28, 020702 (2025).

FEL transverse phase & source point retrieval (2023)

- We suggested that the FEL red–shifted tranverse phase was V–shaped [1]

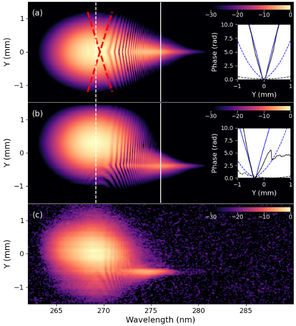
(due to an inheritage from SR, inheritage known, V–shape not)



[1] M. Labat et al., Phys. Rev. Research 7, 023061 (2025).

FEL transverse phase & source point retrieval (2023)

- And we observed the signature of this V–shaped phase on the fringes...
- ... Observed fringes are not smoothly curved, but triangularly shaped [1]

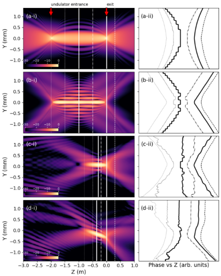


[1] M. Labat et al., Phys. Rev. Research 7, 023061 (2025).

FEL transverse phase & source point retrieval (2023)

More...

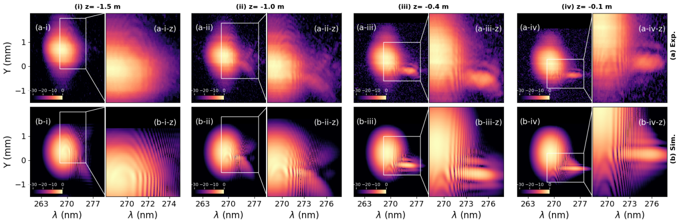
- Back–propagating a V–shaped phase wavefront...
- ...leads to phase aliasing → giving zeros in intensity = fringes....



- And the cherry is: fringes contrast is maximum at source point...
  → We found a source point retrieval technique...

FEL transverse phase & source point retrieval (2023)

- Back–propagating our FEL wavefront with our imaging system...
- ...We observed the fringes AND their maximum contrast location
- Our source point was at z=-0.4 m before undulator exit [1]



[1] M. Labat et al., Phys. Rev. Research 7, 023061 (2025).

FEL transverse phase & source point retrieval (2023)

$\rightarrow$ we could produce very refined FEL physics on an LPA...

... benefitting a "stable" beam ($>$ 5 hours per day)

COXINEL next steps (2025–202?)

- Implement an XUV spectrometer....
  ... to try observation of FEL harmonics (at 90 and 54 nm)
- Characterize the FEL pulse duration via interferometric reconstruction [1]

[1] M. Labat et al., New J. Phys. 22, 013051 (2020).

Conclusion

Conclusion

- LPA based FELs are still in the early development phase

  → On RFAs: proposed 1971, first X-ray FEL 2010 = 40 years development...

  → Proposed 2007, first lasing 2021 = 14 years development...

- Maybe LPAs' stability will never reach RFAs'...

  → because of intrinsic physics ?...

- But there might be room for applications:

  → Less stability / high repetition rate demanding...

  → ...But requiring compactness for more easy access

- COXINEL keeps trying to pave a path...

  ... towards users compatible LPA based FELs

→ First signal in a seeded configuration, tunability studies, refined FEL physics, exponential growth regime in a seeded configuration

Conclusion

Thank you for your attention...

→ Questions ?

COXINEL team @HZDR