Accelerator-based **coherent** lightsources in extreme wavelength range

Eléonore Roussel

Univ. Lille, CNRS, UMR 8523 - PhLAM - Physique des Lasers, Atomes et Molécules, Lille, FRANCE

Journées Accélérateurs SFP
Roscoff, octobre 2023

Curriculum Vitae

2011/09 - 2014/09 Doctorat dans le groupe de dynamique non-linéaire du laboratoire PhLAM à Lille: étude des instabilités spatio-temporelles apparaissant dans les paquets d'électrons relativistes dans les anneaux de stokage.

2014/10 - 2017/04 Post-doc dans le groupe accélérateur du laser à électrons libes (LEL) FERMI en Italie: étude de la dynamique du faisceau d'électrons relativistes et génération de rayonnement cohérent dans les EUV.

2017/05 - 2017/09 Post-doc à Synchrotron SOLEIL sur le projet COXINEL de laser à électrons libres sur accélération plasma: génération de rayonnement LEL à partir de faisceaux d'électrons générés par accélération laser-plasma.

2017/10 - Present **Chargée de Recherche CNRS** au laboratoire PhLAM.

2017 International Young FEL prize

2022 Médaille de Bronze CNRS

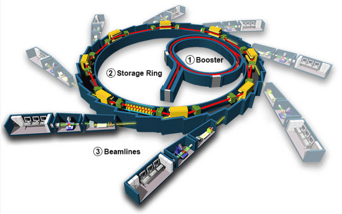
Research group

- PhLAM
  - part of DYSCO team (DYnamique des Systèmes COmplexes)
    - Serge Bielawski
    - Christophe Szwaj
    - Clément Evain (**Prix Jean-Louis Laclare 2017**)
    - Marc Le Parquier (IR - CERLA)
    - Christelle Hanoun (PhD student - 3rd year)
    - Quentin Demazeux (PhD student - 2nd year)

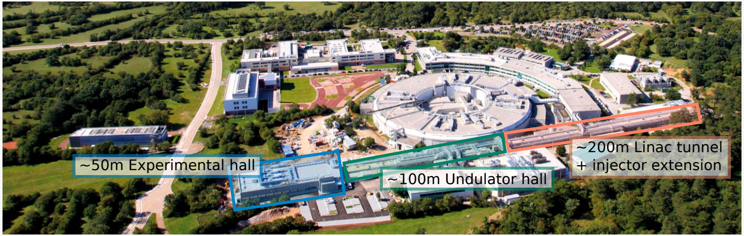
- In collaboration with several accelerator teams:
  - Synchrotron SOLEIL, France
  - KARA, Karlsruhe Institute of Technology, Germany
  - DESY, Hamburg, Germany
  - FERMI, Trieste, Italy
  - ELBE/HZDR, Dresden, Germany
  - COXINEL project, (ERC - Sycnhrotron SOLEIL) France
  - TWAC project (EIC - IJCLab), France

Accelerator-based lightsources: Storage Rings vs. Free-Electron Lasers

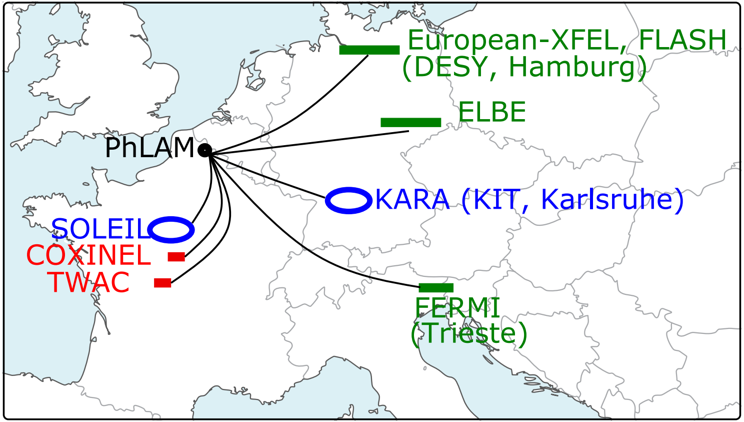
Storage rings: e.g. Synchrotron SOLEIL (France), KARA (Karlsruhe, Germany)...



Free-Electron Lasers: e.g. FERMI (Trieste, Italy), European XFEL (Hamburg, Germany)...



→ Relativistic e-beam of **few GeV** — Radiation from **THz to X-rays**.



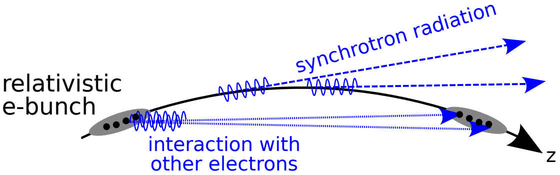
Projects:

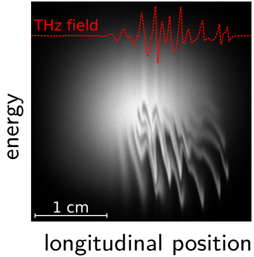
- CNRS Momentum METEOR
- ANR ULTRASYNC
- EIC TWAC

Collaborations on:

- Ultra-fast electron bunch and THz diagnostics
- Electron bunch dynamics
- New accelerator generations
- Coherent sources

Relativistic electron beam behind synchrotron radiation emission





BUT... microbunching instability

- interaction between e$^-$ and their radiation ⇒ microbunching instability
- Formation of microstructures (from mm to μm scale)
  ⇒ source of intense coherent THz radiation
  ⇒ degradation of electron beam properties
- Irregular evolution in space and time

⇒ ☹ Major limitation for the operation of coherent FELs at ultra short wavelengths.

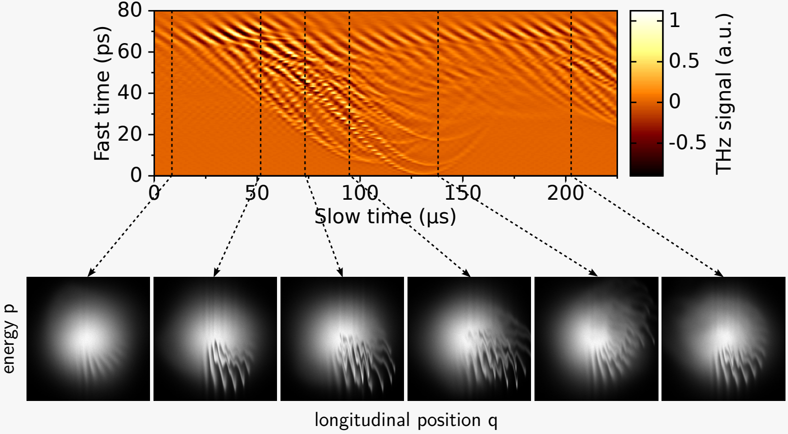
⇒ ☺ New source of coherent radiation in the THz domain in storage rings.

PhD thesis: modeling of the electron bunch dynamics

Equation Vlasov-Fokker-Planck (1D)

$$\frac{\partial f}{\partial \theta} - p\frac{\partial f}{\partial q} + [q - I_c E_{wf}]\frac{\partial f}{\partial p} = 2\varepsilon \frac{\partial}{\partial p}\left(pf + \frac{\partial f}{\partial p}\right)$$

From phase-space to THz emission

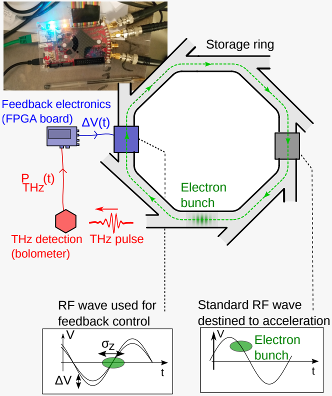


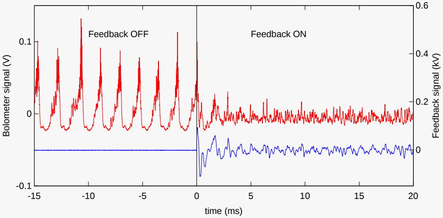
Simulations: SOLEIL @$I = 15$ mA, $\approx$ 20 min/32 proc., national GENCI center

Control of the microbunching instability at Synchrotron SOLEIL

[**Evain**, Szwaj, Roussel, Rodriguez, Le Parquier, Tordeux, Ribeiro, Labat, Hubert, Brubach, Roy, Bielawski, Nature Physics **15**, 635 (2019)]

Feedback control inspired from chaos control strategy

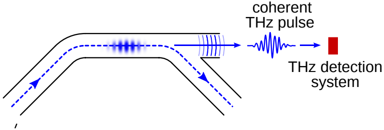




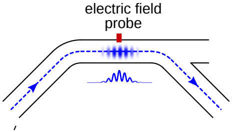
- Apparently simple: required additional hardware: $400 FPGA board
- Involved strategy borrowed from chaos control theory: the so-called OGY method [Ott, Grebogi & Yorke, PRL, **64**, 1196 (1990)]
- Stabilization of a pre-existing solution: major consequence: the required power → **0** once the transient have disappeared (power involved at SOLEIL is a fraction of MEGAWATT !)

PhD thesis: observation challenges

Far field: detection of coherent THz radiation

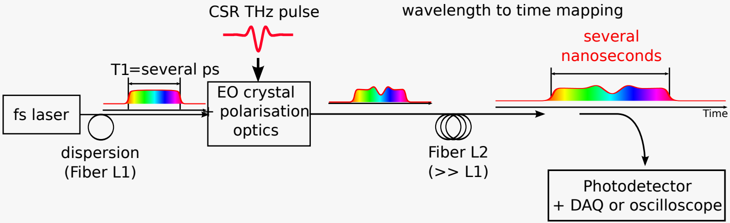


Near field: detection of electron bunch shape



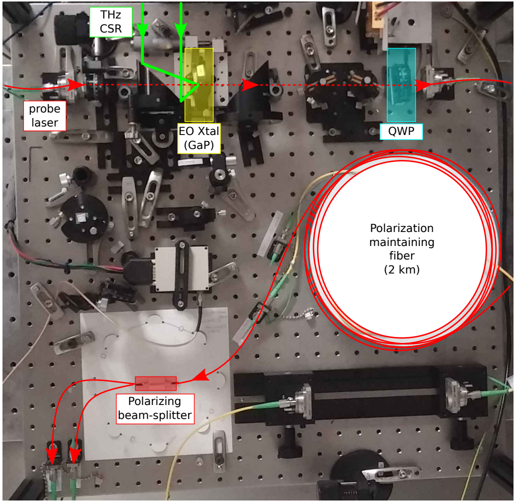
Needs of: (i) speed (sub-ps resolution), (ii) single-shot operation, (iii) >MHz rep. rate, ...

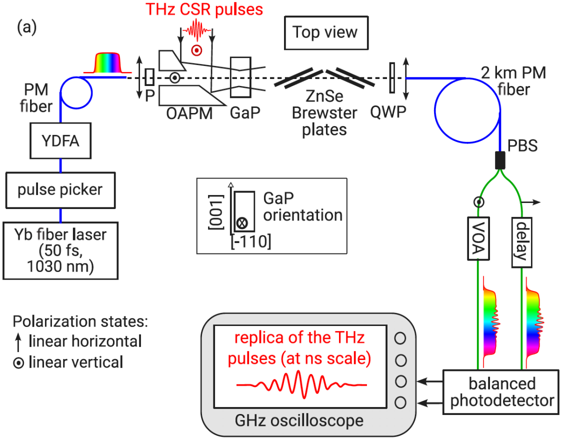
The "PhLAM strategy":
electro-optic sampling [Zhang et al., APL (1998)] + photonic time-stretch [Jalali et al., Electronics Letters (1998)]



Detection of a "copy" of the THz pulse slowed down by a factor $M = 1 + L_2/L_1$.

(Typical: $L_1 = 10$ m, $L_2 = 2$ km $\rightarrow M \sim 200$, i.e. 5 GHz on the oscilloscope $\equiv$ 1 THz at the input).

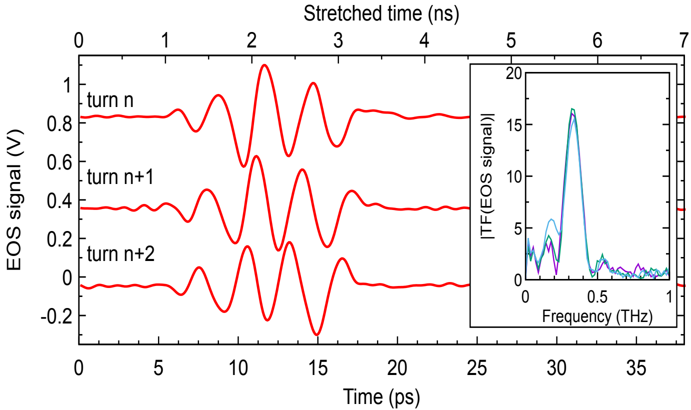




[Roussel et al., Scientific Reports **5**, 10330 (2015)]] [Szwaj et al., Rev. Sci. Instrum. **87**, 103111 (2016)], [Evain et al., PRL **118**, 054801 (2017)]

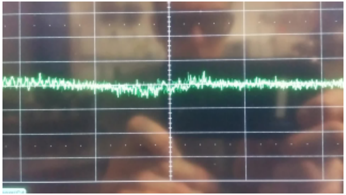
Successive single-shot CSR pulses recordings

THz CSR electric field from 1 bunch at every turn (i.e. every ≈ μs)



5 GHz low-pass filtering
→ 1 THz limitation
(stretch factor = 200)

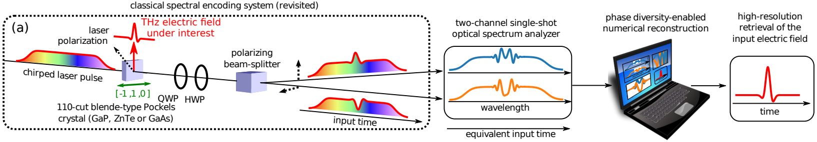
Synchrotron SOLEIL, nominal-alpha operation,
(I = 12 mA, 15 ps RMS, normal user operation)

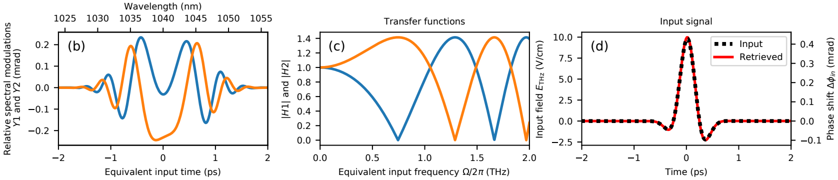


METEOR solves a 20 year old problem on the temporal resolution of single-shot EO detection of electric field:

$$\tau = \sqrt{t_{laser} \times t_{window}}$$

e.g. $t_{laser} = 100$ fs and $t_{window} = 10$ ps $\rightarrow \tau = 1$ ps » t_{laser} ☹
$\rightarrow$ [Roussel, et al. Phase Diversity Electro-optic Sampling: A new approach to single-shot terahertz waveform recording. Light Sci Appl **11**, 14 (2022)]

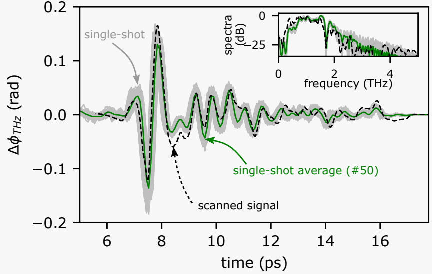




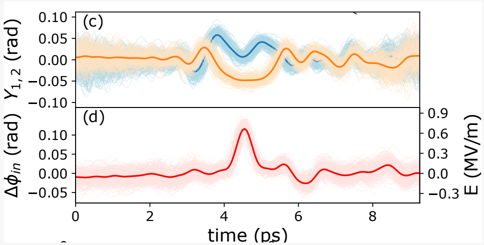
Applications of phase-diversity electro-optic sampling

- TeraFERMI –> low rep. rate, high peak power coherent THz radiation on FEL
- EuXFEL –> access to single shot electron bunch profile with near field setup
- Synchrotron SOLEIL –> high rep. rate with high average THz power (access to the microbunching dynamics)
- FELBE –> THz FEL at high rep. rate (access to the enveloppe and carrier of the radiation !)
- ... Opens door to single-shot Time-Domain Spectroscopy

Single-shot TDS at TeraFERMI

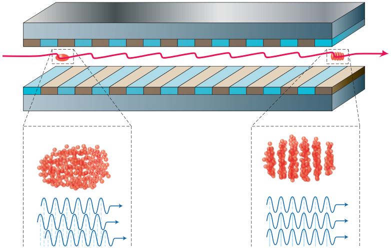


Bunch profiles at EuXFEL



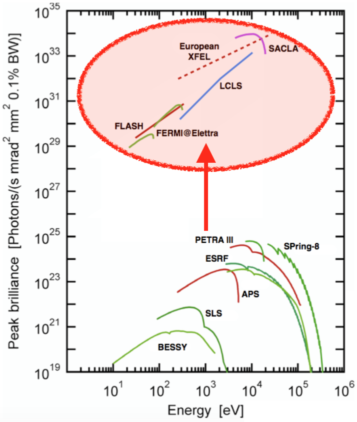
Research activities on Single-pass Free-Electron Laser: collaboration with FERMI (Italy)

Principle: amplification, up to saturation, of the radiation produced by a relativistic electron beam travelling in an periodic magnetic field (i.e. undulator)



[McNeil & Thompson, Nat. Photon. 239 (2010)]

- relativistic electrons: energy $\sim$ GeV
- high quality ebeams
- high peak current $\sim$ kA
- bunch length $\sim 1 - 100$ fs
- peak power $\sim$ GW

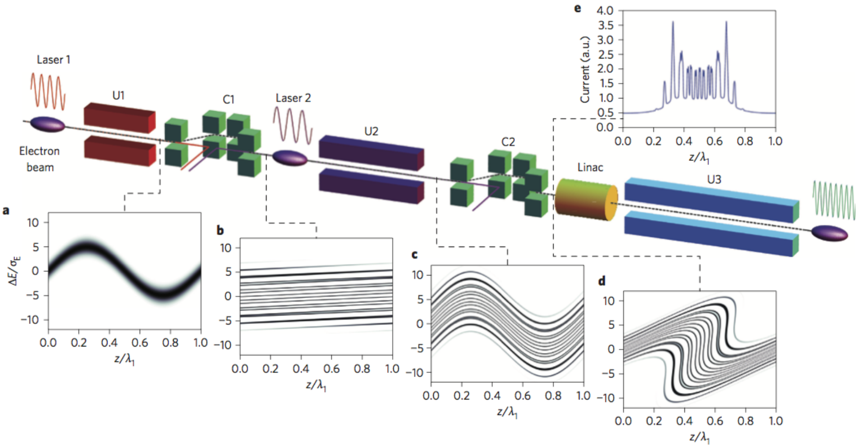


[Schmüser et al., Free-Electron Lasers in the Ultraviolet and X-Ray Regime, Springer, (2014)]

Challenge: generation of coherent, ultra-short pulse in the x-rays domain

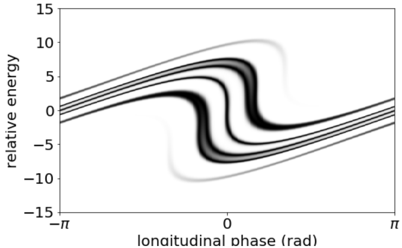
The beam-echo effect: Echo-Enabled Harmonic Generation (EEHG)

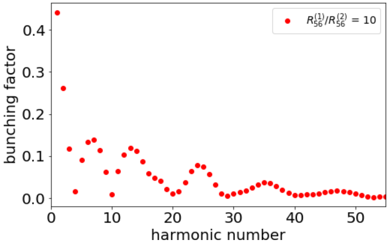
Strongly nonlinear harmonic up-conversion process based on a two-seed laser interaction
$\rightarrow 1/\lambda_R = n/\lambda_1 + m/\lambda_2$ [G. Stupakov, Phys. Rev. Lett. **102**, 074801 (2009)]



[Hemsing et al., Nat. Photon. 10, 512–515 (2016)]

Bunching factor and phase-space evolution





more beamlets in the phase-space → higher harmonic in the bunching factor ☺

Benefits of EEHG

- small energy modulation needed,
- from UV to soft x-ray in one stage,
- tunable,
- less sensitive to ebeam quality, ...

Challenges

- preservation of fine phase space structure ?
- sensitivity to intrabeam scattering, diffusion and laser quality ?

Experimental demonstration of EEHG: time-lapse

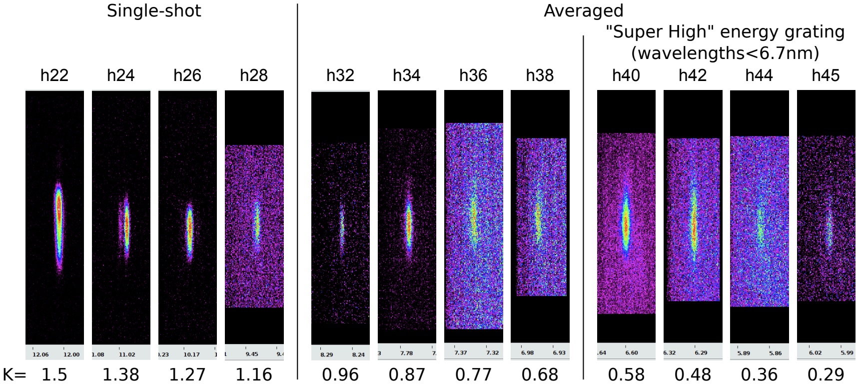
- **2009** first theory of beam-echo effect [G. Stupakov, Phys. Rev. Lett. **102**, 074801 (2009)], [D. Xiang and G. Stupakov, Phys. Rev. STAB, **12**, 030702 (2009)]
- **2010** 3rd harmonic observation + coherent emission (NO FEL !) [D. Xiang et al., Phys. Rev. Lett. **105**, 114801 (2010))]
- **2012** 3rd harmonic + amplification [Z. T. Zhao et al., Nature Photonics **6**, 360–363 (2012)]
- **2014** 15th harmonic (NO FEL !) [E. Hemsing et al., Phys. Rev. STAB **17**, 070702 (2014)]
- **2016** 75th harmonic (NO FEL !) [E. Hemsing et al., Nature Photonics **10**, 512–515 (2016)]

→ still no FEL based on EEHG in the soft x-ray domain ?!

- **2017** calculation of EEHG @FERMI in the soft x-ray domain [P. R. Rebernik, E. Roussel, G. Penn, G. De Ninno, L. Giannessi, G. Penco, E. Allaria, Echo-Enabled Harmonic Generation Studies for the FERMI Free-Electron Laser. Photonics **2017**, 4, 19]

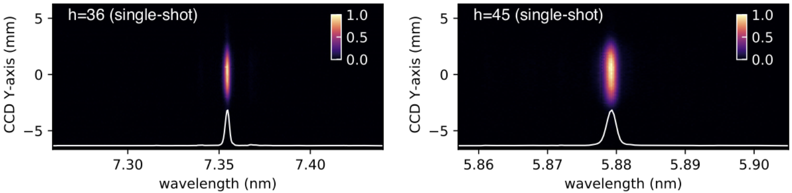
EEHG @FERMI: medium harmonic range

- “low-energy” beam (≈ 900 MeV, i.e. low gain for $h > 30$)

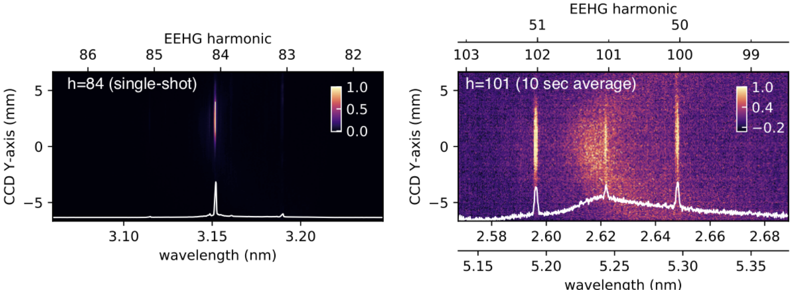


EEHG @FERMI: high harmonics

- with e-beam at max. energy (≈ 1.5 GeV), very high harmonics up to **101**



using high sensitivity EUV CCD from Andor:



FERMI FEL collaboration

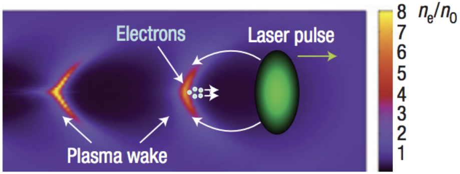
- [2019-2021] MOU between FERMI and PhLAM
  - → FEL physics: demonstration of EEHG

[P. Ribic et al, Nat. Photonics (2019)]

  - → electron beam dynamics: study of microbunching instability

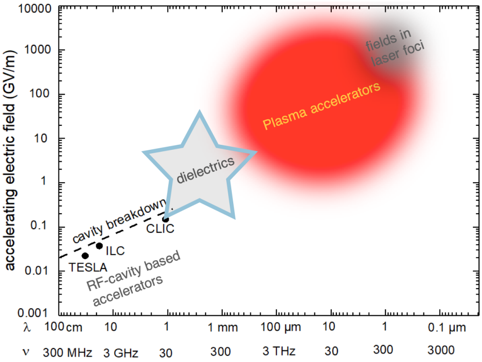
- [2019-2021] CNRS Momentum METEOR: application to TeraFERMI
- [2021-2023] Elettra Distinguished Young Scientist
  - → study and characterization of the microbunching instability and its impact on the FEL radiation properties
  - → development of FERMI-FEL for the generation of harmonics below 2 nm.

Towards compact accelerator: Laser-plasma accelerators - Dielectric accelerators



- Accelerating electric field in ionized plasma:

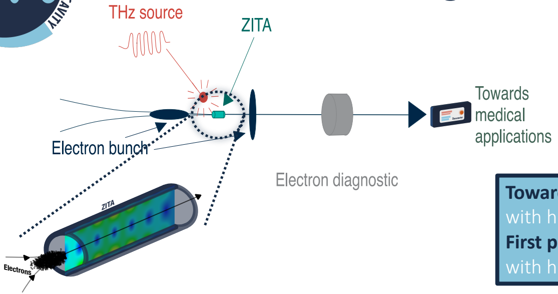
$$E_0(\mathrm{V/m}) \simeq 96\sqrt{n_0(\mathrm{cm}^{-3})}$$



plasma density of $n_0 \approx 10^{18}$ cm^{-3}
$\rightarrow E_0 \simeq 100$ GV/m $\gg 10's$ MV/m in conventional radio-frequency (rf) linear accelerators (LINACs)
$+$ potential to produce extremely short electron bunches., $\tau_b \ll 100$ fs.

[E. Esarey, et al., RevModPhys.81.1229 (2009)], [B. Hidding, et al., arXiv:1904.09205 (2019)]

TWAC – EIC Pathfinder (2022-2026)
Terahertz Waveguide Accelerating Cavity



European Innovation Council

Towards compact accelerators
with high gradient & high peak current
First prototype of 1-m scale kA accelerator
with high frequency industrial cavity

Partners & expertise:

- **CNRS/IJCLab:** Accelerator physics + TWAC prototype
- **CNRS/PhLAM:** Beam dynamics and ultrafast THz/electron diagnostics
- **CSIC:** Dosimetry, FLASH radiotherapy
- **DESY:** Electron diagnostics + test facility for benchmarks
- **iTEOX**: Valorisation
- **University of Pécs:** High power THz source
- **RadiaBeam:** Valorisation

Le projet COXINEL: de l'accélération laser-plasma vers un laser à électrons libres injecté par un laser externe

Eléonore Roussel
on behalf of the COXINEL team

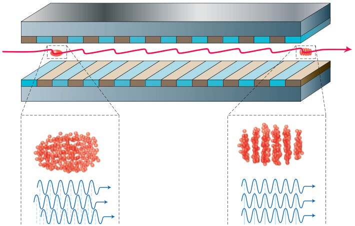
Univ. Lille, CNRS, UMR 8523 - PhLAM - Physique des Lasers, Atomes et Molécules, Lille, FRANCE

Journées Accélérateurs SFP
Roscoff, octobre 2023

Single-pass Free-Electron Laser

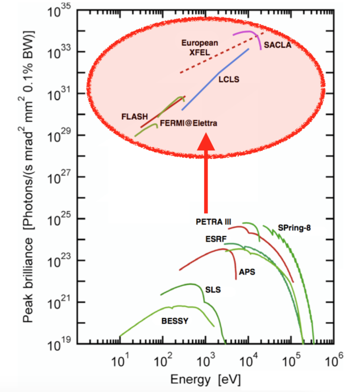
Principle amplification, up to saturation, of the radiation produced by a relativistic electron beam travelling in a periodic magnetic field (i.e. undulator)

Radiation resonance condition: $\lambda_R = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$



[McNeil & Thompson, Nat. Photon. 239 (2010)]

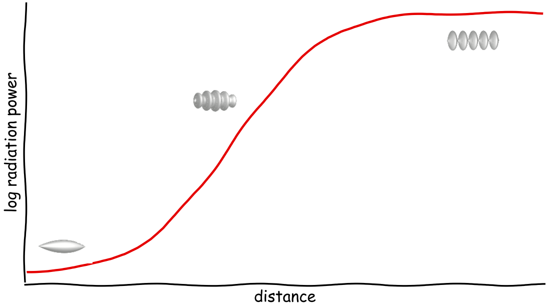
- relativistic electrons: energy $\sim$ GeV
- high quality ebeams
- high peak current $\sim$ kA
- bunch length $\sim 1 - 100$ fs
- peak power $\sim$ GW



[Schmüser et al., Free-Electron Lasers in the Ultraviolet and X-Ray Regime, Springer, (2014)]

Free-electron laser amplification

- electron beam / optical wave interaction $\rightarrow$ energy exchange
- microbunching at radiation wavelength λ_R $\rightarrow$ coherent emission
- coherent emission exponentially amplified $\rightarrow$ FEL
- loss of energy, increase of energy spread $\rightarrow$ out-of-resonance, saturation



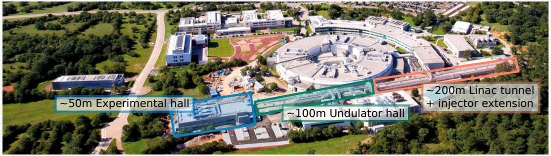
- FEL Pierce parameter $\rho \propto (I/(\sigma_x \sigma_y))^{1/3}$
- Power $P \propto \exp(z/L_g)$
- Gain length $L_g \propto \left(1 + \sigma_\delta^2/\rho^2\right)/\rho$
- Saturation length $L_s \approx 22 \times L_g$
- For high-gain FEL: $\sigma_\delta \ll \rho$

[K.J. Kim and M. Xie, NIMA **331**, 359 (1993)]

Some existing FEL facilities

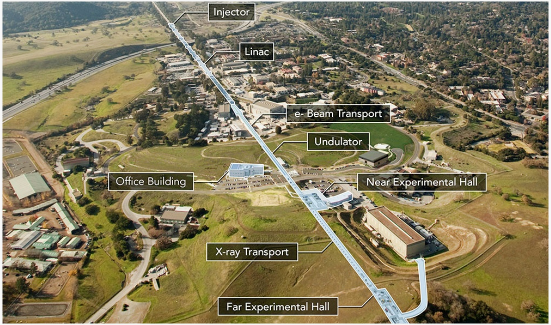
Example (1): FERMI (Italy)

- 200 m LINAC + 100 m undulator line
- energy ~ 1.5 GeV $\rightarrow \gamma \sim 3000$
- $K_u \sim [1 - 7.5]$ and $\lambda_u = 55/35$ mm
- $\rightarrow \lambda_R \sim [4 - 100]$ nm

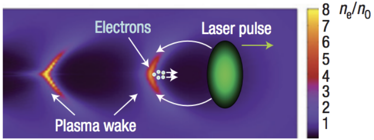


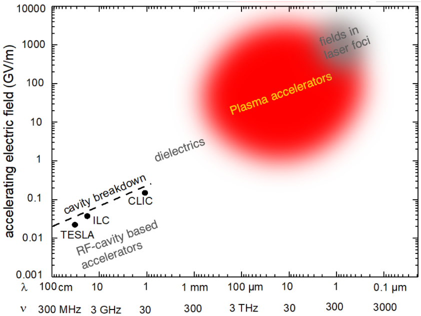
Example (2): LCLS (USA)

- 1 km LINAC + 132 m undulator line
- $K_u = 3.5$ and $\lambda_u = 30$ mm
- energy ~ 14 GeV $\rightarrow \gamma \sim 28000$
- $\rightarrow \lambda_R = 1.4$ Å



Towards compact accelerator: Laser-plasma accelerators (LPAs)



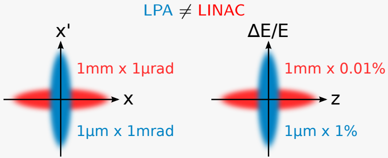


- Accelerating electric field in ionized plasma:

$$E_0(\mathrm{V/m}) \simeq 96\sqrt{n_0(\mathrm{cm}^{-3})} \quad \text{with } n_0 \approx 10^{18}\mathrm{cm}^{-3}$$

$\rightarrow E_0 \simeq 100$ GV/m $\gg$ 10's MV/m in conventional RF LINAC
$+$ potential to produce extremely short e- bunches $<$ 100 fs.

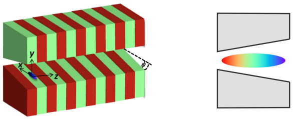
[E. Esarey, et al., RevModPhys.81.1229 (2009)], [B. Hidding, et al., arXiv:1904.09205 (2019)]



How to deal with LPA large divergence & energy spread ?

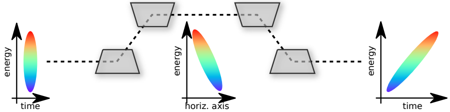
LPA-based FEL: strategies to fulfil the requirement $\sigma_\delta \ll \rho$ for high-gain FEL

- transverse-gradient undulator



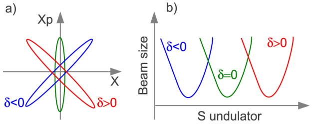
[Z. Huang, et al., Phys. Rev. Lett. **109**, 204801 (2012)]

- demixing chicane

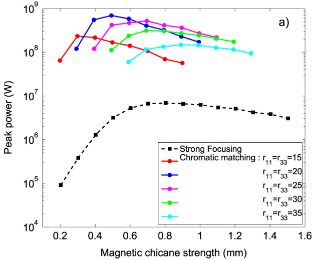


[M.E. Couprie, et al., J. of Phys. B: AMO Phys. **47**, 234001 (2014)],
[A.R. Maier et al., Phys. Rev. X **2**, 031019 (2012)]

- super-matching

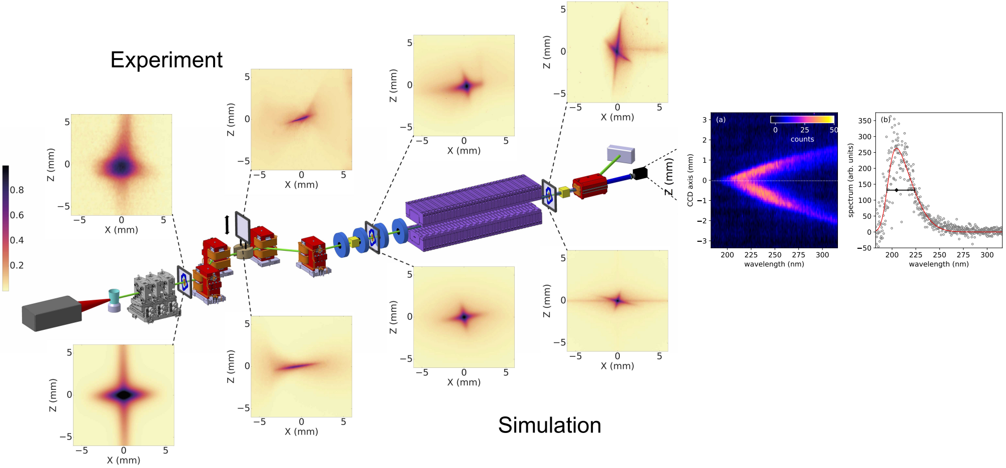


[A. Loulergue et al., New Journal of Physics **17**, 023028 (2015)]



COXINEL: Towards a LPA-based FEL demonstrator

COherent X-ray source INferred from Electrons accelerated by Laser
→ Free Electron Laser demonstrator using an electron beam produced by laser-plasma acceleration.



COXINEL collaboration

- ERC Advanced Grant COXINEL, PI: M.E. Couprie (Synchrotron SOLEIL) 2014-2019
- COXINEL: collaboration SOLEIL - LOA - PhLAM

  → electron beam transport
  [T. André et al., Nature Communications **9**, 1334 (2018)]
  [D. Oumbarek Espinos et al., Plasma Phys. Control. Fusion **62**, 034001 (2020)]

  → spontaneous emission of undulator radiation
  [A. Ghaith et al., Scientific Reports 9, 19020 (2019)]
  [E. Roussel et al., Plasma Phys. Control. Fusion **62** 074003 (2020)]

  → theory on LPA-based FEL
  [M. Labat, ..., E. Roussel, New J. Phys. **22** 013051 (2020)]

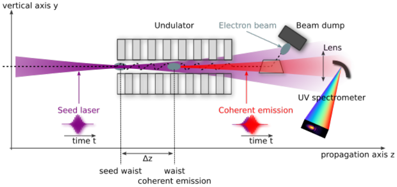
but NO FEL... divergence was too high, charge density was too low !

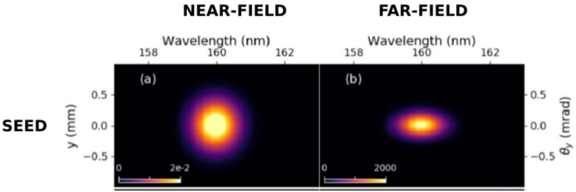
- COXINEL#2 (2021-2022): collaboration SOLEIL - HZDR (Dresden) + PhLAM, LOA

  → demonstration of first seeded FEL amplification based on LPA
  [M. Labat et al., Nature Photonics **17**, 150-156 (2023)]

Numerical calculation of a seeded LPA-based FEL

Typical observable:
spatio-spectral distribution
on a 2D UV spectrometer

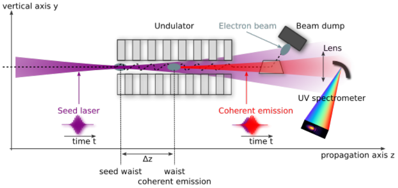


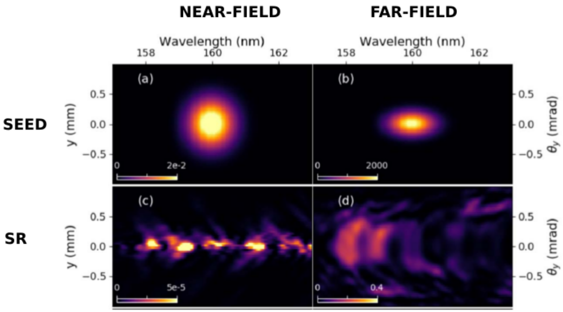


[M. Labat, ..., E. Roussel, New J. Phys. **22** 013051 (2020)]

Numerical calculation of a seeded LPA-based FEL

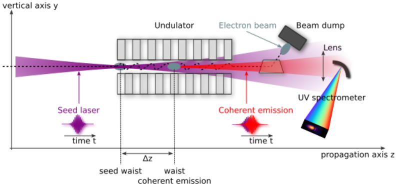
Typical observable:
spatio-spectral distribution
on a 2D UV spectrometer

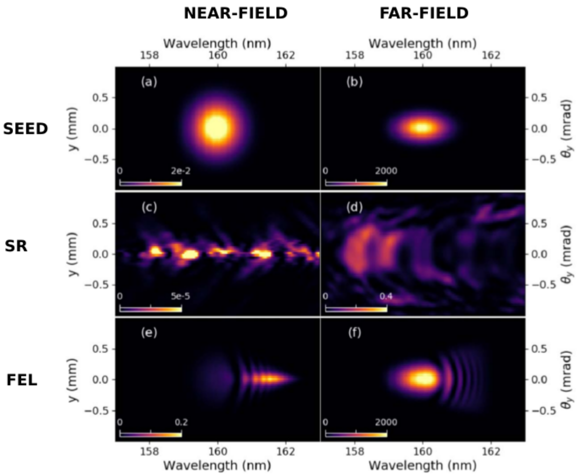




Numerical calculation of a seeded LPA-based FEL

Typical observable:
spatio-spectral distribution
on a 2D UV spectrometer

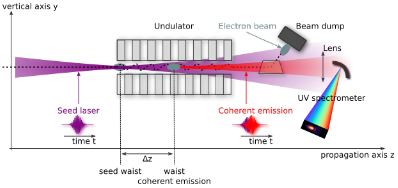




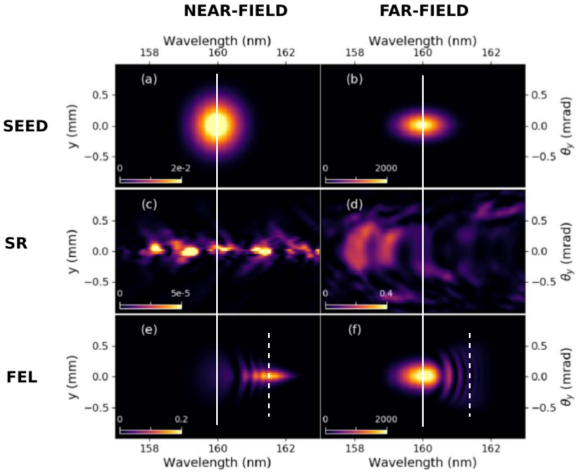
[M. Labat, ..., E. Roussel, New J. Phys. **22** 013051 (2020)]

Numerical calculation of a seeded LPA-based FEL

Typical observable:
spatio-spectral distribution
on a 2D UV spectrometer

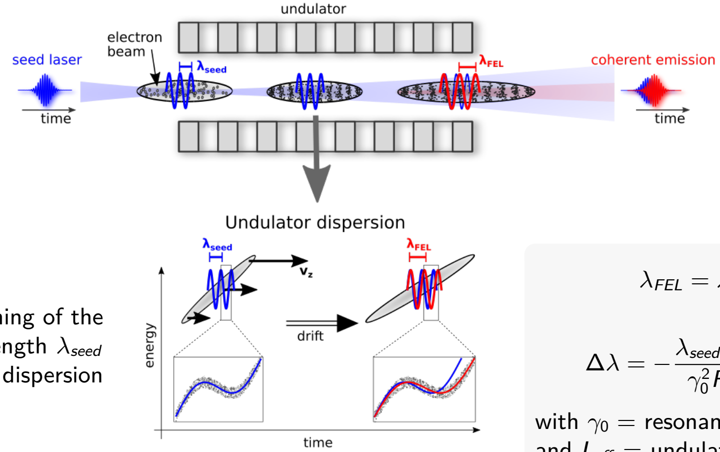


- FEL emission is **red-shifted** w.r.t. seed wavelength
- Presence of **interference fringes**



[M. Labat, ..., E. Roussel, New J. Phys. **22** 013051 (2020)]

Origin of the red-shifted emission



stretching of the modulation wavelength λ_{seed} by undulator dispersion

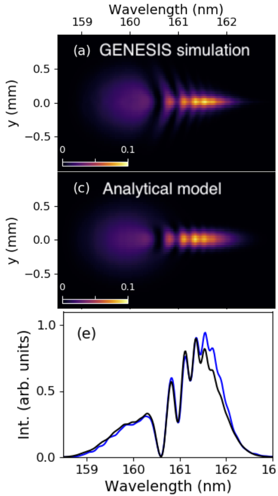
$$\lambda_{FEL} = \lambda_{seed} + \Delta\lambda$$

$$\Delta\lambda = -\frac{\lambda_{seed} L_{eff}}{\gamma_0^2 R_{56}} \left(1 + \frac{K_u^2}{2}\right)$$

with γ_0 = resonant energy
and L_{eff} = undulator effective length

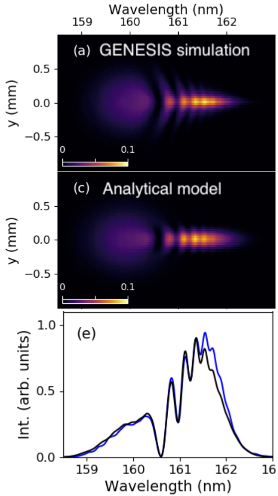
Interference fringes from two coherent pulses

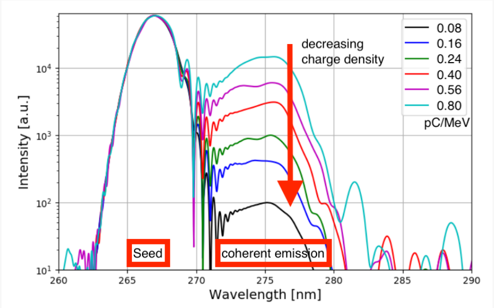
In case of low gain, the FEL pulse is the sum of 2 pulses at $\neq$ wavelength,
$\rightarrow$ FEL $=$ seed $+$ coherent emission



Interference fringes from two coherent pulses

In case of low gain, the FEL pulse is the sum of 2 pulses at $\neq$ wavelength,
$\rightarrow$ FEL $=$ seed $+$ coherent emission

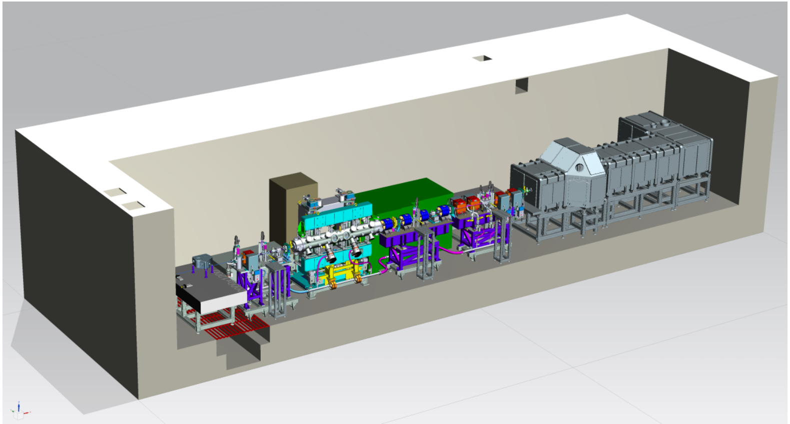


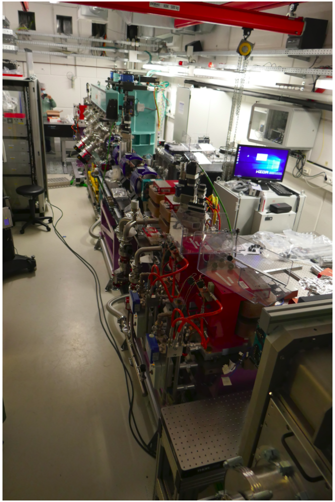


thanks to **red-shift + fringes**
$\rightarrow$ detection of very low FEL signals

COXINEL @ HZDR (Dresden, Germany)

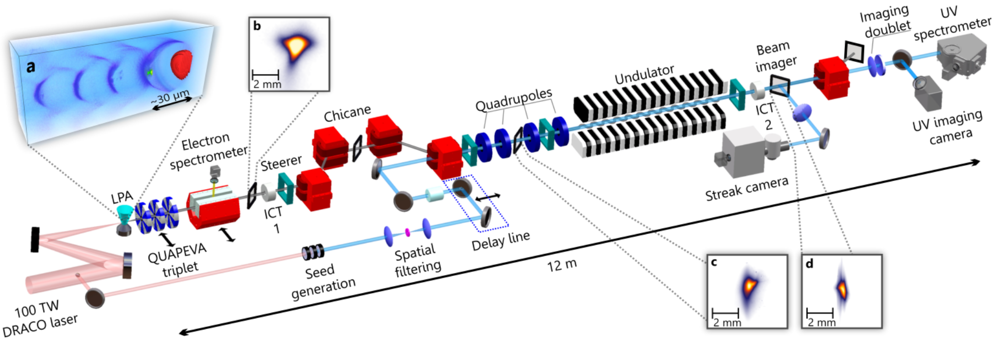
→ Oct. 2021: COXINEL beamline moved into 111c LPA cave of HZDR

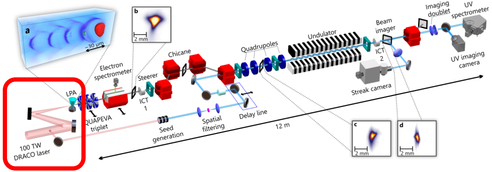




→ "A perfect fit"

COXINEL beamline

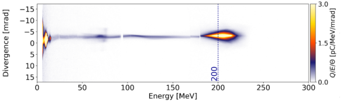


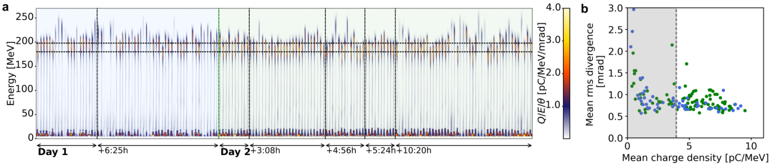


- 100 TW–class arm of IR DRACO laser
- Tailored self-truncated ionization-induced injection scheme
- Beam loading to limit energy spread

[A. Irman et al., Plasma Phys. Control. Fusion **60**, 044015 (2018)], [J.P. Couperus et al., Nat. Comm. **8**, 487 (2017).]

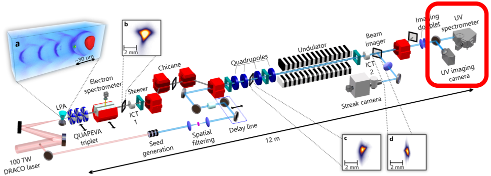
Single shot spectrometer acquisition /// Electron beam records over two days of FEL experiment



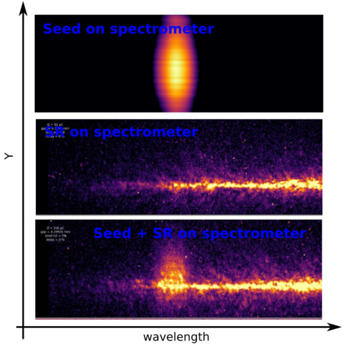


- Charge density: 5–10 pC/MeV
- Divergence: < 1 mrad–rms
- Emittance: ≈ 1 mm.mrad
- Stability: $>$**8 hours stable** operation + **day–to–day reproducible** properties

Photon & FEL diagnostics



Spatio-spectral overlap between seed and SR



Streak camera

- Model: FESCA–100 (Hamamatsu)
- Radiation extracted at undulator exit using an Aluminium mirror

→ Adjustment of seed / SR temporal overlap

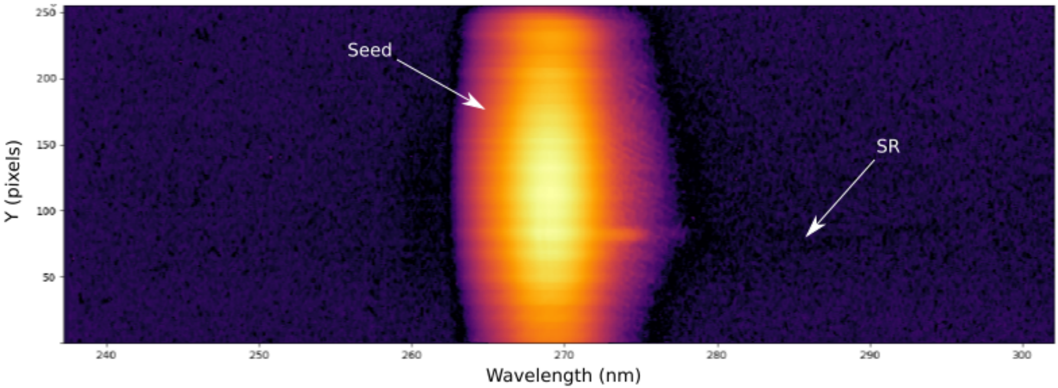
2D UV spectrometer

- iHR320 from Horiba/Jobin-Yvon with a 2D UV-camera

→ SR spatio–spectral distribution (Y vs λ)

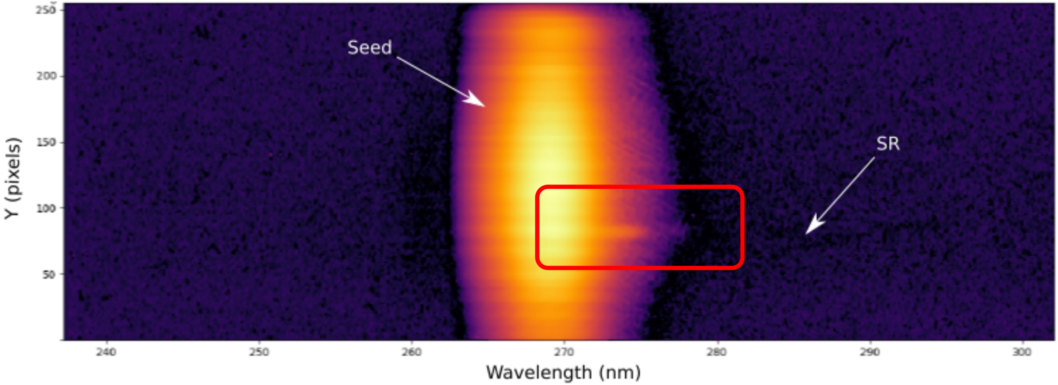
→ Seed / SR spatio–spectral alignment

During the first delay scan...

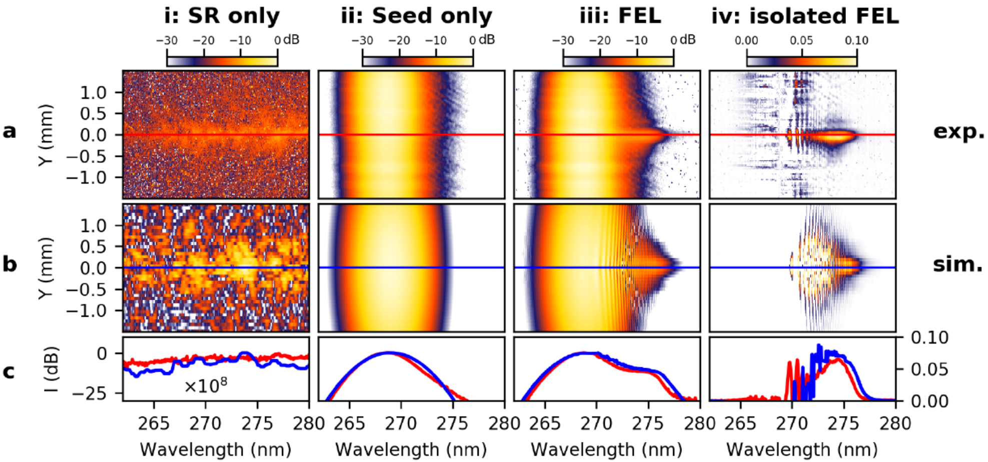


First FEL signal

During the first delay scan...



First FEL signal ! Tiny... but **red–shifted** (as expected) → ☺

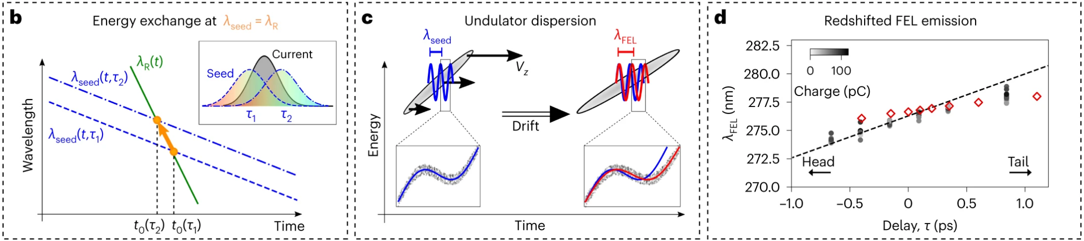


→ **FEL observation confirmed** with shifted by ≈ 5 nm (red–shift and fringes as in theory)

[M. Labat et al., Nature Photonics **17**, 150-156 (2023)]

FEL spectral control

A specificity of chirped seed FEL: spectral control with seed delay



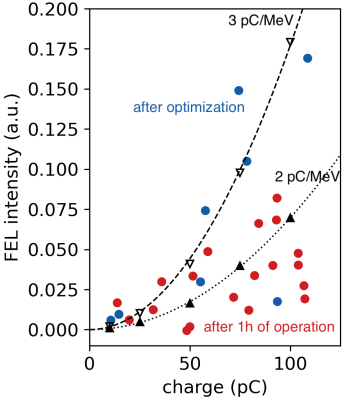
$$\lambda_R(t) = \frac{\lambda_u}{2\gamma(t)^2}\left(1 + \frac{K_u^2}{2}\right) \quad \rightarrow \quad \lambda_{FEL} = \left(\lambda_0 + \frac{t_0 - \tau}{D_\lambda}\right) \times \left(1 + \frac{1 + K_{u0}^2/2}{\gamma(t_0)^2 R_{56}} L_{eff}\right)$$

$$\lambda_{seed}(t) = \lambda_0 + \frac{t - \tau}{D_\lambda}$$

Resonance only occurs at t_0 where $\lambda_R(t_0) = \lambda_{seed}(t_0)$

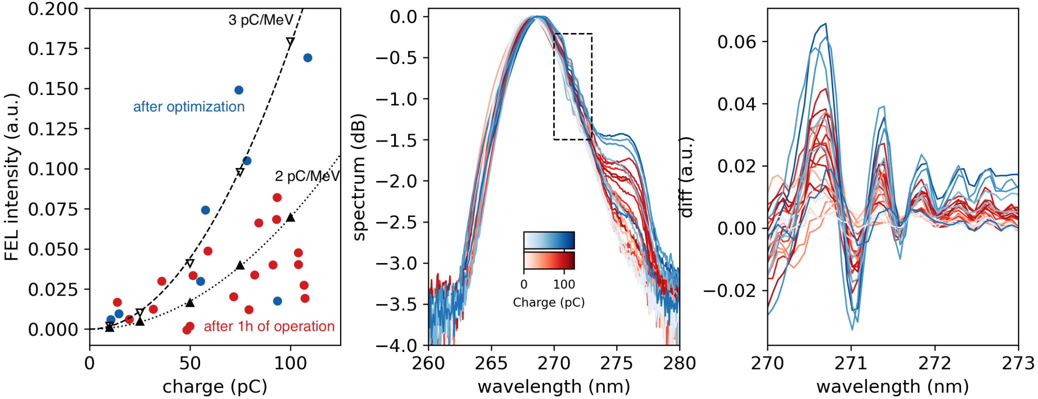
Coherent emission

- A basic proof of temporal coherence is the **quadratic charge dependency** of FEL pulse energy.



[M. Labat et al., Nature Photonics **17**, 150-156 (2023)]

1. A basic proof of temporal coherence is the **quadratic charge dependency** of FEL pulse energy.
2. A strong proof of temporal coherence is **phase-locked interference fringes**.



[M. Labat et al., Nature Photonics **17**, 150-156 (2023)]

Conclusion

Achievements on LPA-based FEL

- Several teams have been racing since a decade to demonstrate the feasability of an LPA based FEL
- Recently: 3 teams succeeded in a lapse of 1 year !
  - SASE FEL based on laser plasma accelerator
    [Wang, W., Feng, K., Ke, L. et al., Nature **595**, 516-520 (2021)]
  - SASE FEL based on beam-driven plasma wakefield accelerator
    [Pompili, R., Alesini, D., Anania, M.P. et al., Nature **605**, 659-662 (2022)]
  - seeded FEL based on beam-driven plasma wakefield accelerator
    [M. Galletti et al. Phys. Rev. Lett. **129**, 234801 (2022)]
- The "+" of COXINEL: $\rightarrow$ proof of spectral control & temporal coherence !

Next steps

- @ short term
  - Improve stability and repetition rate of LPA source.
  - Spectro-temporal reconstruction of the FEL pulses from interference pattern.
- @ long term
  - FEL towards shorter wavelength.
  - Initial target of COXINEL: 40 nm.

Acknowledgments