



**HAL**  
open science

## **Progress Towards Laser Plasma Electron Based Free Electron Laser on COXINEL**

Marie-Emmanuelle Couprie, Thomas André, Igor Andriyash, Chamseddine Benabderrahmane, Serge Bielawski, Frederic Blache, Francois Bouvet, Fabien Briquez, Sebastien Corde, Yannick Dietrich, et al.

► **To cite this version:**

Marie-Emmanuelle Couprie, Thomas André, Igor Andriyash, Chamseddine Benabderrahmane, Serge Bielawski, et al.. Progress Towards Laser Plasma Electron Based Free Electron Laser on COXINEL. 39th International Free Electron Laser Conference, Aug 2019, Hamburg, Germany. pp.THP048, 10.18429/JACoW-FEL2019-THP048 . hal-02497844

**HAL Id: hal-02497844**

**<https://hal.science/hal-02497844>**

Submitted on 17 Aug 2020

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# PROGRESS TOWARDS LASER PLASMA ELECTRON BASED FREE ELECTRON LASER ON COXINEL

M. E. Couprie \*, T. André, F. Blache, F. Bouvet, F. Briquez, Y. Dietrich, J. P. Duval, M. El-Ajjouri, A. Ghaith, C. Herbeaux, M. Khojoyan, N. Hubert, C. Kitégi, M. Labat, N. Leclercq, A. Lestrade, A. Loulergue, O. Marcouillé, F. Marteau, D. Oumbarek Espinos, P. Rommeluère, M. Sebdaoui, K. Tavakoli, M. Valléau, Synchrotron SOLEIL, GIF-sur-YVETTE, France  
C. Benabderrahmane, ESRF, Grenoble, France  
S. Corde, J. Gautier, J. P. Goddet, O. Kononenko, G. Lambert, A. Tafzi, K. Ta Phuoc, C. Thaury, Laboratoire d'Optique Appliquée, Palaiseau, France  
S. Bielawski, C. Evain, E. Roussel, C. Szwaj, Laboratoire PhLAM, Villeneuve d'Ascq, France  
I. Andriyash, V. Malka, S. Smartzev, Weizmann Institute, Rehovot, Israel

## Abstract

Laser plasma acceleration (LPA) [1] with up to several GeV beam in very short distance appears very promising. The Free Electron Laser (FEL), though very challenging, can be viewed as a qualifying application of these new emerging LPAs. The energy spread and divergence, larger than from conventional accelerators used for FEL, have to be manipulated to answer the FEL requirements. On the test COXINEL experiment [2–4] line, "QUAPEVA" permanent magnet quadrupoles of variable strength [5, 6] handle the emittance growth and a decompression chicane reduces the slice energy spread, enabling FEL amplification for baseline reference parameters [2]. A beam pointing alignment compensation method enables to properly transport the electrons along the line, with independent adjustments of position and dispersion [7]. The measured undulator spontaneous emission radiated exhibits the typical undulator radiation pattern, and usual features (gap tunability, small linewidth...).

## INTRODUCTION

Accelerator based light sources presently know a very wide development [8], with the FEL [9] advent in the X-ray domain [10] coming along with an increase of the peak brightness by several orders of magnitude, enabling fifty years after the laser invention [11] to decipher the matter structure in unexplored areas and dynamics on ultra-fast time scales unraveling the processes involved various domains [12]... Following the laser invention, alternately of developing FELs relying on non bounded relativistic electrons in an undulator periodic permanent magnetic field as a gain medium [9], laser have been considered to generate and accelerate electrons in plasmas [1]. An intense laser focused onto a gas target ionizes the gas and creates a plasma. As the laser pulse propagates, the ponderomotive force expels electrons from the optical axis, forming a cavity free of electrons in the laser wake with large amplitude electric fields where electrons can be trapped and accelerated. With the growth of ultra high power laser making advantage of Chirped Pulse Amplification techniques [13],

electrons can be accelerated with plasma up to several GeV within ultra-short distances [14–16] with kA peak current, ultra-short bunches,  $1\pi$  mm.mrad normalized emittance beams, enabling to consider LPA to drive an FEL [3, 17]. Even though some LPA features such as peak current and emittance seem to be quite suitable for the FEL application, energy spread and divergence do not meet conventional accelerator  $\mu$ rad divergence and per mille of energy spread beams. They should be handled to mitigate chromatic effects [18, 19], that can lead to a dramatic emittance growth and afferent beam quality degradation in the transfer lines. Large divergence requires strong focusing right after the electron source, with for instance high gradient permanent magnet quadrupoles [20]. Large energy spread can be managed by a decompression chicane [3, 21] or a transverse gradient undulator [22, 23]. The energy-position correlation introduced by the chicane [2] can be turned into an advantage. There are still very few experiments with LPA electron beam transport towards an undulator [24] and preliminary observation of undulator radiation [25–28]. The COXINEL program [29] aiming at demonstrating FEL amplification using a dedicated manipulation line is developed in the frame of the LUNEX5 project of advanced compact free electron laser demonstrator [30, 31]. We report here the progress on the COXINEL experimental program.

## THE COXINEL LINE DESIGN

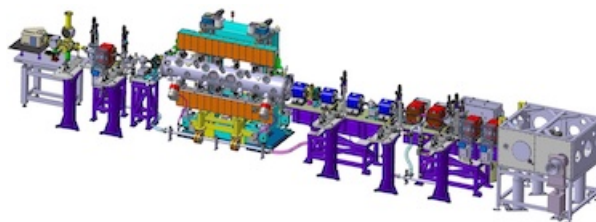


Figure 1: COXINEL line CATIA sketch.

The COXINEL line (see Fig. 1) has been designed and built at Synchrotron SOLEIL [4, 32] (ERC Advanced COXINEL 340015) using the baseline reference parameters given in Table 1 for the 180 MeV case, for being installed at Labora-

\* couprie@synchrotron-soleil.fr

toire d'Optique Appliquée (LOA). The divergence is rapidly mitigated (5 cm away from the source) via strong focusing with a triplet of QUAPEVA permanent magnet based quadrupoles of variable strength (with rotating cylindrical magnet surrounding a central Halbach ring quadrupole [33]) and adjustable magnetic center position (with translation tables) [5,6]. A magnetic chicane then longitudinally stretches the beam, sorts electrons in energy and selects the energy range of interest via a removable and adjustable slit mounted in the middle of the chicane. A second set of quadrupoles matches the beam inside an in-vacuum undulator. Electron diagnostics include current transformers, cavity beam position monitors and removable scintillator screens for electron profile imaging [34]. The "200 MeV" corresponds to radiation in the UV with a 2 m long cryo-ready undulator U18 (period 18 mm) [35], while the 400 MeV case associated to the U15 cryogenic undulator enables to reach the VUV spectral range. The line equipments have been characterized [4, 32].

The electron transport [36] images the electron source in the undulator. The total emittance growth is frozen at the QUAPEVA triplet exit. The "supermatching optics" focuses each electron beam slice in synchronisation with the progression of the amplified synchrotron radiation along the undulator, taking advantage of the energy - position correlation introduced in the chicane, and enables to achieve FEL amplification with the baseline reference parameters [2]. The sensitivity study of the FEL versus different parameters has been carried out [37]. Other optics (focusing on the screens for transport tuning, focusing vertically in the chicane equipped to select the energy of interest with a slit) are also available.

Table 1: COXINEL baseline reference case at the source and undulator (Und.), measured (Meas.) beam at the source.

Parameter (unit)	Baseline Source	Und.	Meas. Source
Vert. divergence (mrad)	1	0.1	1.2-5
Hor. divergence (mrad)	1	0.1	1.8-7.5
Beam size ( $\mu\text{m}$ )	1	50	
Bunch length (fs RMS)	3.3	33	
Charge (pC)	34	34	
Charge density (pC/MeV)	5	0.5	0.2-0.5
Peak Current (kA)	4.4	0.44	
Energy spread RMS %	1	0.1	>10
Norm. emittance $\epsilon_N$ (mm.mrad)	1	1.7	

## COXINEL MEASUREMENTS

LPA is operated in ionisation injection [38] for robustness with the LOA 1.5 J, 30 FWHM fs pulse laser is focused into a supersonic jet of  $He - N_2$  gas mixture. Electron energy distribution (see Fig. 2 (left)) is broad and ranges up to 250

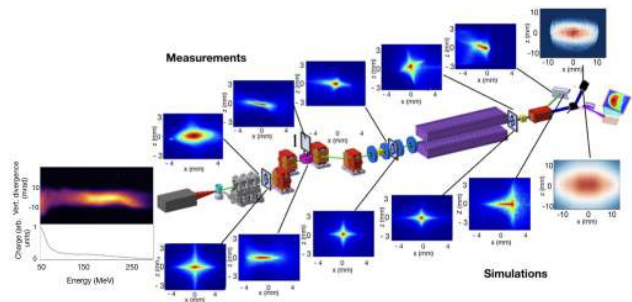


Figure 2: COXINEL electron and photon beam measurements compared to simulations using measured electron beam distribution as an input. Left : electron beam spectrometer measurements and transverse distributions along the line. Right : undulator radiation transverse pattern.

MeV, with a much lower charge density at the energy of interest and larger divergences than expected (see Table 1).

Besides prior alignment of the line components within  $\pm 100 \mu\text{m}$  on the same axis with a laser tracker, and optics daily alignment with a green reference laser, the LPA electron beam pointing (of the order of 1.5 mrad RMS) makes critical the electron beam transport along the line. Thus, a matrix response beam pointing alignment compensation method taking advantage of the "QUAPEVA" adjustable magnetic center and gradient is applied : the electron position and dispersion are independently adjusted [7] step by step along the screens enabling a proper transport along the line. The QUAPEVA strength is slightly adjusted to optimize the focusing thanks to the rotation of the QUAPEVA cylindrical magnets. The matched transported beam measurements are well reproduced with simulations for measured beam characteristics (see Fig. 2), with cross-like shaped focused beam due to chromatic effects and measured tilted beams due to skew quadrupolar terms, that have been further corrected [39].

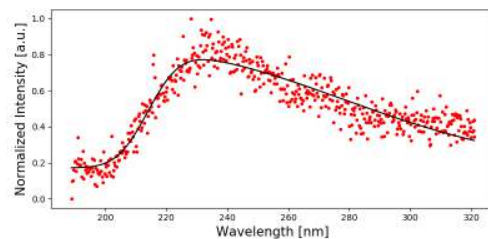


Figure 3: Undulator spectral flux measured with the Horiba iHR 320 spectrometer at 5 mm gap ( 3 mm electron slit).

The radiation from the 2 m long 107 x 18.16 mm periods U18 is then characterized while applying an optics enabling to select a small energy range centered onto the energy of interest with the slit inserted in the magnetic chicane. A typical spectrum is presented Fig. 3, and 2D measured and simulated transverse patterns are displayed in Fig. 2. The undulator radiation (resonant wavelength, intensity) has been tuned by changing the gap. The radiation linewidth can be

controlled using the electron beam energy selection via the slit in the chicane. The estimated full number of photons per beam charge  $N_{ph}$  is  $\approx 3.10^7$  pC<sup>-1</sup>.

## CONCLUSION

We have demonstrated a proper LPA electron beam transport on COXINEL, handling its performance for a FEL application. We have then observed at the end of the line undulator radiation exhibiting the usual characteristics in terms of spatio-spectral distribution, wavelength dependence with gap, spectral purity. The observation of an FEL effect seems possible, provided electron beam measured parameters get closer to the baseline reference case ones [40].

## ACKNOWLEDGMENTS

The authors thank European Research Council (ERC) for COXINEL (340015, P. I. M. E. Couprie), X-Five (339128, PI: V.Malka), the EuPRAXIA design study (653782), the Fondation de la Cooperation Scientifique (QUAPEVA-2012-058T) and for the support of SOLEIL and LOA staff.

## REFERENCES

[1] T. Tajima and J. M. Dawson, "Laser electron accelerator", *Phys. Rev. Lett.*, vol. 43, p. 267–270, Jul 1979. doi:10.1103/PhysRevLett.43.267

[2] A. Loulergue *et al.*, "Beam manipulation for compact laser wakefield accelerator based free-electron lasers", *New Journal of Physics*, vol. 17, no. 2, p. 023028, 2015. doi:10.1088/1367-2630/17/2/023028

[3] M. E. Couprie *et al.*, "Towards a free electron laser based on laser plasma accelerators", *J. Phys. B: Atomic, Molecular and Optical Physics*, vol. 47, no. 23, p. 234001, 2014. doi:10.1088/0953-4075/47/23/234001

[4] M. E. Couprie *et al.*, "An application of laser-plasma acceleration: towards a free-electron laser amplification," *Plasma Phys. Cont. Fusion*, vol. 58, no. 3, p. 034020, 2016. doi:10.1088/0741-3335/58/3/034020

[5] F. Marteau *et al.*, "Variable high gradient permanent magnet quadrupole (QUAPEVA)", *Applied Physics Letters*, vol. 111, p. 253503, 2017. doi:10.1063/1.4986856

[6] A. Ghaith *et al.*, "Tunable high gradient quadrupoles for a laser plasma acceleration based FEL", *Nucl. Instrum. Meth. A*, vol. 909, p. 290-293, 2018. doi:10.1016/j.nima.2018.02.098

[7] T. André, T. *et al.* "Control of laser plasma accelerated electrons for light sources", *Nat. Comm.*, vol. 9, pp. 1334, 2018. doi:10.1038/s41467-018-03776-x

[8] M. E. Couprie, J. M. Filhol, "X radiation sources based on accelerators", *Comptes Rendus Phys.*, vol. 9:487–506, 2008. doi:10.1016/j.crhy.2008.04.001

[9] J. M. Madey, "Stimulated emission of Bremsstrahlung in a periodic magnetic field", *Jour. Appl. Phys.*, vol. 42, p. 1906–1913, 1971. doi:10.1063/1.1660466

[10] P. Emma *et al.*, "First lasing and operation of an Ångstrom-wavelength free-electron laser", *Nature Photonics*, vol. 4, p. 641, 2010. doi:10.1038/nphoton.2010.176

[11] A. L. Schawlow and C. H. Townes, "Infrared and optical masers", *Physical Review*, vol. 112, no. 6, p. 1940, 1958. doi:10.1103/PhysRev.112.1940

[12] C. Bostedt *et al.*, "Linac Coherent Light Source: The first five years", *Rev. Mod. Phys.*, vol. 88 (1), p. 015007, 2016. doi:10.1103/RevModPhys.88.015007

[13] D. Strickland and G. Mourou, "Compression of amplified chirped optical pulses", *Optics communications*, vol. 55, no. 6, p. 447-449, 1985. doi:10.1016/0030-4018(85)90120-8

[14] E. Esarey, C. Schroeder, and W. Leemans, "Physics of laser-driven plasma-based electron accelerators", *Reviews of Modern Physics*, vol. 81, no. 3, p. 1229, 2009. doi:10.1103/RevModPhys.81.1229

[15] V. Malka *et al.*, "Laser-driven accelerators by colliding pulses injection: A review of simulation and experimental results", *Physics of Plasmas*, vol. 16, no. 5, p. 056703, 2009. doi:10.1063/1.3079486

[16] W. P. Leemans *et al.*, "Multi-GeV electron beams from capillary-discharge-guided subPetaWatt laser pulses in the self-trapping regime", *Phys. Rev. Lett.*, vol. 113, p. 245002, 2014. doi:10.1103/PhysRevLett.113.245002

[17] F. Gruner *et al.*, "Design considerations for table-top, laser-based VUV and X-ray free electron lasers", *Appl. Phys. B*, vol. 86, p. 431-435, 2007. doi:10.1007/s00340-006-2565-7

[18] K. Floettmann, "Some basic features of the beam emittance", *Phys. Rev. ST Accel. Beams*, vol. 6, p. 034202, 2003. doi:10.1103/PhysRevSTAB.6.034202

[19] M. Migliorati *et al.*, "Intrinsic normalized emittance growth in laser-driven electron accelerators", *Phys. Rev. ST Accel. Beams*, vol. 16, p. 011302, 2013. doi:10.1103/PhysRevSTAB.16.011302

[20] A. Ghaith *et al.*, "Permanent Magnet-Based Quadrupoles for Plasma Acceleration Sources", *Instruments*, vol. 3, no. 2, pp. 27, 2019. doi:10.3390/instruments3020027

[21] A. Maier *et al.*, "Demonstration scheme for a laser-plasma-driven free-electron laser", *Physical Review X*, vol. 2, no. 3, p. 031019, 2012. doi:10.1103/PhysRevX.2.031019

[22] T. I. Smith *et al.*, "Reducing the sensitivity of a free-electron laser to electron energy", *Journal of Applied Physics*, vol. 50, no. 7, pp. 4580–4583, 1979. doi:10.1063/1.326564

[23] Z. Huang, Y. Ding, C. B. Schroeder "Compact X-ray free-electron laser from a laser-plasma accelerator using a transverse-gradient undulator", *Phys. Rev. Lett.*, vol. 109, no. 20, pp. 204801, 2012. doi:10.1103/PhysRevLett.109.204801

[24] C. Widmann *et al.*, "Beam transport system from a laser wakefield accelerator to a transverse gradient undulator", *Proceed. IPAC conf., Dresden, Germany*, p. 2803, 2014. doi:10.18429/JACoW-IPAC2014-THOBA03

[25] H. P. Schlenvoigt *et al.*, "A compact synchrotron radiation source driven by a laser-plasma wakefield accelerator", *Nature Physics*, vol. 4, no. 2, pp. 130–133, 2008. doi:10.1038/nphys811

[26] M. Fuchs *et al.*, "Laser-driven soft-X-ray undulator source," *Nature physics*, vol. 5, no. 11, pp. 826–829, 2009. doi:10.1038/nphys1404



- [27] G. Lambert *et al.*, "Progress on the generation of undulator radiation in the UV from a plasma-based electron beam", *Proceed. FEL conf., Nara, Japan, Aug. 2012*, paper THPD47, pp. 638-641.
- [28] M.P. Anania *et al.*, "An ultrashort pulse ultra-violet radiation undulator source driven by a laser plasma wakefield accelerator", *Appl. Phys. Lett.*, vol. 104, no. 26, pp. 264102, 2014. doi:10.1063/1.4886997
- [29] M. Couprie *et al.*, "Experiment preparation towards a demonstration of laser plasma based free electron laser amplification", in *Proc. 36th Int. Free Electron Laser Conf. (FEL'14)*, Basel, Switzerland, Aug. 2014, paper TUP086, pp. 569-573.
- [30] M.-E. Couprie *et al.*, "The LUNEX5 project in France", *Jour. of Physics: Conf. Series*, vol. 425, no. 7, pp. 072001, 2013. doi:10.1088/1742-6596/425/7/072001
- [31] M. Couprie *et al.*, "Strategies towards a compact XUV free electron laser adopted for the LUNEX5 project", *Journal of Modern Optics*, vol. 63, no. 4, pp. 1-13, 2015. doi:10.1080/09500340.2015.1075617
- [32] M. E. Couprie *et al.*, "Towards free electron laser amplification to qualify laser plasma acceleration", *The review of laser engineering*, vol. 45, no. 2, pp. 94-98, 2017.
- [33] K. Halbach *et al.*, "Design of permanent multipole magnets with oriented rare earth cobalt material," *Nucl. Instrum. Meth.*, vol. 169, p. 1-10, 1980. doi:10.1016/0029-554X(80)90094-4
- [34] M. Labat *et al.*, "Electron and photon diagnostics for plasma acceleration-based FELs", *Journal of synchrotron radiation*, vol. 25, no. 1, p. 59-67, 2018. doi:10.1107/S1600577517011742
- [35] C. Benabderrahmane *et al.* "Development and operation of a  $Pr_2Fe_{14}B$  based cryogenic permanent magnet undulator for a high spatial resolution x-ray beam line", *Phys. Rev. Acc. Beams*, vol. 20, no. 3, p. 033201, 2017. doi:10.1103/PhysRevAccelBeams.20.033201
- [36] M. Khojayan *et al.*, "Transport studies of LPA electron beam towards the FEL amplification at COXINEL", *Nucl. Instrum. Meth. A*, vol. 829, no. 2, pp. 260-264, 2016. doi:10.1016/j.nima.2016.02.030
- [37] M. Labat *et al.*, "Robustness of a plasma acceleration based Free Electron Laser", *Phys. Rev. Acc. Beams*, vol. 21, no. 11, pp. 114802, 2018. doi:10.1103/PhysRevAccelBeams.21.114802
- [38] C. McGuffey *et al.*, "Ionization induced trapping in a laser wakefield accelerator", *Phys. Rev. Lett.*, vol. 104, no. 2, p. 025004, 2010. doi:10.1103/PhysRevLett.104.025004
- [39] D. Oumbarek-Espinos *et al.*, "Skew quadrupole effect of laser plasma electron beam transport", *Applied Science*, vol. 9, no. 12, p. 2447, 2019. doi:10.3390/app9122447
- [40] M. Labat *et al.*, "Interferometry for full temporal reconstruction of laser-plasma accelerator-based seeded free electron lasers", *ArXiv 1906.11140v2*, 2019.