ELECTRON TRANSPORT ON COXINEL BEAM LINE*

T. Andre†, I. Andriyash, F. Blache, F. Bouvet, F. Briquez, M.-E. Couprie, Y. Dietrich, J.-P. Duval, M. El-Ajjouri, A. Ghaith, C. Herbeaux, N. Hubert, M. Khojoyan, M. Labat, N. Leclercq, A. Lestrade, A. Loulergue, O. Marcouillé, F. Marteau, P. Ngotta, P. Rommeluere, E. Roussel, M. Sebdaoui, K. Tavakoli, M. Valléau, SOLEIL, Gif-sur- Yvette, France
S. Corde, J. Gautier, J.-P. Goddet, G. Lambert, B. Mahieu, V. Malka, S. Smartzev, C. Thaury, LOA, Palaiseau, France
S. Bielawski, C. Evain, C. Szwaj, PhLAM/CERLA, Villeneuve d'Ascq, France

Abstract

COXINEL experiment aims at demonstrating free electron laser (FEL) amplification with a laser plasma accelerator (LPA). For COXINEL, a dedicated 8 m transport line has been designed and prepared at SOLEIL. We present here LPA beam transport results around 180 MeV through this line. Different electron beam optics were applied.

INTRODUCTION

Today, LPAs [1–3] can deliver, over only few millimeters, relativistic electron beams of few femtosecond duration and high peak current in the multi-kiloAmps range with energies from hundreds MeV to few GeV [4]. While transported and accelerated in the plasma wave, electrons acquire significant dispersion of the transverse and longitudinal momenta, leading to degradation of beam quality along the transport. For COXINEL [5–10], specific methods were developed and applied to control the transport [11] and beam properties for FEL applictation.

COXINEL

The COXINEL electron beam transport line for FEL was designed at SOLEIL, where the magnetic elements where carefully modelled and measured. The experiment is installed and aligned with the laser line of the "Salle Jaune" laser facility of Laboratoire d'Optique Appliquee (LOA) as shown in Fig. 1.

The laser plasma acceleration is achieved with a 800 nm, 30 fs, 30 PW laser pulse which is delivered to the interaction chamber where the laser is focused to a spot of $10 - 15\,\mu$m size in the supersonic jet of a gas mixture composed of 99% of Helium and 1% of Nitrogen. In such a set-up, electrons are injected into the laser wake via self-injection and ionization injection mechanisms [12]. This method of production (Broad Band i.e. BB) creates an electron beam with high divergence (≈ 3 mrad rms) and a wide energy spectrum (50 MeV to 250 MeV). Shock injection method was also used, in order to reduce the energy spread. In the experimental conditions, significant variations of the beam parameters were observed from shot to shot and also from one day to another.

Table 1: Properties of the Magnetic Equipements Installed on COXINEL

Equipements	Properties	Units	Values
QUAPEVAs	Gradient Variation	%	50
	Maximum Gradient	T/m	200
Dipoles	Yoke Length	mm	200
	Magnetic Field @ 150 A	T	0.55
Quadrupoles	Current	A	10
	Max Gradient	T/m	20
Undulator	Period	mm	18
	Peak field @ Gap 5 mm	T	1.156
	Magnetic Lentgh	m	2

To control the large divergence of the beam, three permanent magnett quadrupoles, so-called QUAPEVA [13], of variable gradient (up to 200 T/m), are placed near the source inside the production chamber. After this refocusing, the electron beam passes in a de-mixing chicane where electrons are sorted in energy in order to reduce the slice energy spread [14–16]. Finally a set of four electromagnetic quadrupoles is installed at the entrance of the undulator [17, 18] to focus the electron beam and enhance the FEL amplification [19]. For electron diagnostics, devices such as turbo-Integrated Current Transformer, cavity Beam Position Monitors, screens, are installed every 1-2 m along the beam line [20]. Table 1 summarizes the specifications of the equipements intalled on COXINEL beam line.

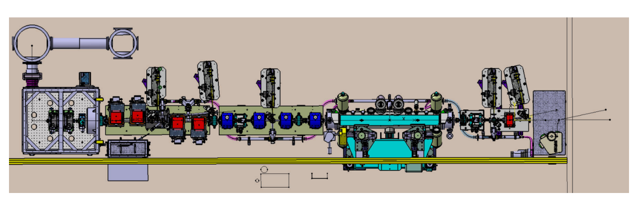

Figure 1: General view of the COXINEL LWFA demonstration set-up. From left to right : LWFA chamber (grey) with the first set of quadrupoles and a current beam transformer, magnetic chicane dipoles (red), quadruplet of quadrupoles (blue), undulator (case of 2 meter U18 undulator), dipole for beam dump (red), UV-spectrometer (brown).

* Work supported by ERC COXINEL (340015)
† thomas.andre@synchrotron-soleil.fr

ELECTRON SOURCE CHARACTERIZATION

A proper characterization of the electron beam properties at the source is crucial to be able to optimize the transport. For that, several parameters, such as energy distribution, beam divergence, have to be checked with different electron diagnostics.

Electron Beam Spectra

The electron beam spectrum is first measured using a small spectrometer (1 T permanent dipole magnet) directly installed after the gas jet. Figure 2a shows a typical 2D raw image where the vertical divergence is plotted versus the horizontal deviation in pixel due to the magnetic field. The spectra are continuous, ranging from 50 MeV (pixel 380) to 220 MeV (pixel 0) and fluctuate from shot to shot. Energy distribution deconvolved with the spectrometer dispersion function is shown in Fig. 2b. The target energy fo transport line is 176 MeV (pixel 80) and was chosen to observe a 200 nm radiation from the U18 at gap 5 mm. In this configuration only vertical divergence can be measured and is estimated to be 13 mrad (FWHM) for the central energy of 175 MeV with fluctuation from 3 to 15 mrad (Figure 2c).

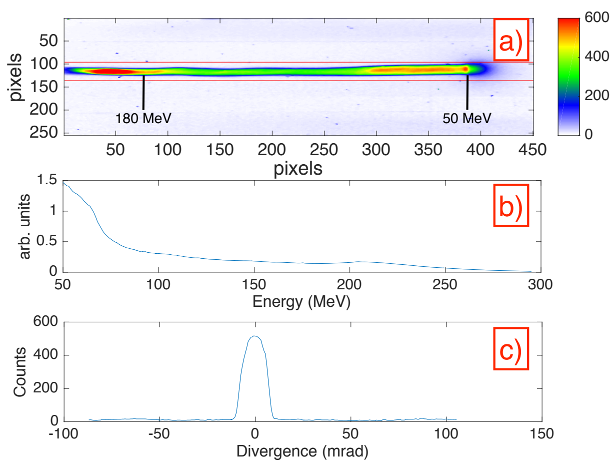

Figure 2: (a) Raw image from the scintillator (LANEX) screen of an electron beam spectrum: Energy (x axis) (from 50 MeV (pixel 380) to 220 MeV) (pixel 0), vertical divergence (z axis). (b) Deconvolved angle-integrated energy spectrum. (c) Vertical divergence at 175 MeV

Transverse Distribution

The horizontal divergence is measured on LANEX screen (localized after the removable QUAPEVAs). Figure 3 shows the beam on screen 1, without QUAPEVAs installed. From this screen, the energy-integrated divergence of the beam, in both planes, is deduced using:

$$\sigma_{x'(z')} = \frac{\sigma_{x(z)}}{D}, \tag{1}$$

with $D = 64$ cm, the distance between the electron source and screen 1, and $\sigma_{x(z)}$ the horizontal (vertical) rms beam size. An observation of the beam on screen 1 is shown in Fig. 3.

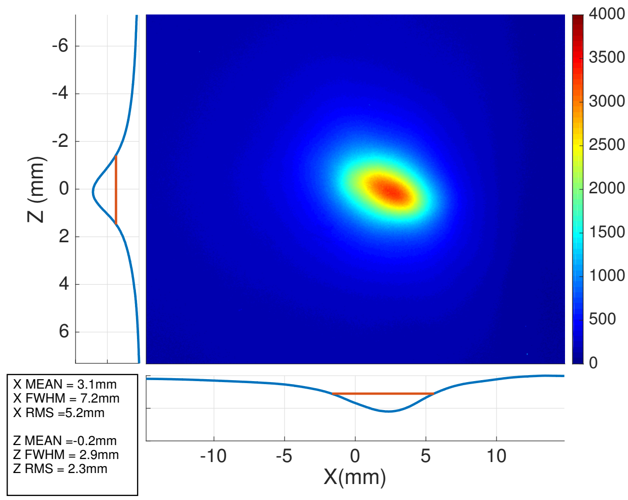

Figure 3: Experimental observation of electron beam on screen 1 without QUAPEVAs: horizontal and vertical profiles (blue), and FWHM beam size (orange).

From the data in Fig. 3, one can deduce the horizontal rms beam divergence with equation (1): $\sigma_{x'}(rms) = (5.2\,\text{mm})/(64\,\text{cm}\,.\sqrt{2}) = 5.7$ mrad. The $\sqrt{2}$ factor comes from a tilt of 45 deg of the screen.

STRONG FOCUSING

Thanks to the QUAPEVAs, which are installed as close as possible to the electron source, the divergence of the electron beam is kept under control. The transverse ditribution of the focused beam has been measured on screen 1 and compared with the simulations (Figure. 4a).

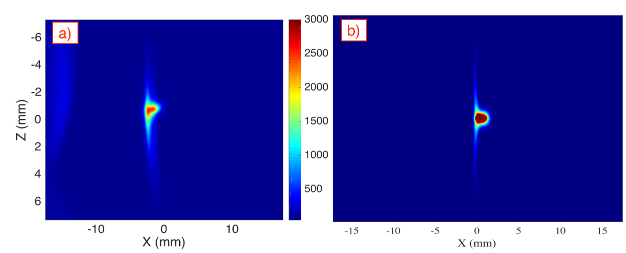

Figure 4: Electron beam focused on screen 1: (a) numerical simulation with a divergence $\sigma_{x'} = \sigma_{z'} = 1$ mrad, $\theta_x = 2$ mrad, E =176 MeV, $\sigma_E = 30\%$, Q =34 pC,
(b) experimental observation.

The simulations and the experiment are in a good agreement and they indicate that adjustments are needed to control the electron beam. Indeed, a 2 mrad angle has been included in the simulation to reproduce the experimental observations (see Fig. 4b). Due to the strong focusing configuration of the QUAPEVAs, a small misalignment of the magnetic centers of the quadrupoles with respect to the beam axis introduces additional dispersion to the electron beam and unwanted kick with respect to the reference trajectory. To reduce these

ISBN 978-3-95450-182-3

side effects, a beam based alignment method was applied on the three QUAPEVAs. Thanks to horizontal and vertical motorized translations installed on the QUAPEVAs, the magnetic centers can be precisely adjusted to minimize the undesirable effects.

ENERGY MEASUREMENT INTO THE CHICANE

The characterization of the electron beam along the transport line is of crucial interest, especially to understand the influence of the QUAPEVAs. The de-mixing chicane permits to measure the electron beam enegy spectrum after the second dipole of the chicane (see Fig. 1). The electron beam is deflected in the first two dipoles and observed on screen 2 (shifted by 32 mm from the reference axis). The propagation through the dispersive sections stretches the beam in the horizontal direction. The calibration of the horizontal axis on screen 2 into energy is given by Eq. (2):

$$E = \frac{L.B.L_{dip}.c}{x_{pos}}, \tag{2}$$

with $L = 0.4$ m the drift length, $L_{dip} = 0.2$ m the dipole length, B the variable magnetic field and x_{pos} the offset position with respect to the reference axis. For the nominal energy of 176 MeV and a magnetic field $B = 0.2$ T, the electron beam is deviated by 32 mm and is observed at the center of screen 2. The deviation is inversely proportional to the energy: an electron with a lower energy is more deviated ($x_{pos} > 32$ mm) while one with a higher energy is less deviated by the magnetic field ($x_{pos} < 32$ mm). Figure 5 shows the energy spectrum measured in the middle of the chicane. As shown in Fig. 5b, the maximum of the energy distribution corresponds to a mean energy of 172 MeV with an energy spread of 20 MeV (FWHM).

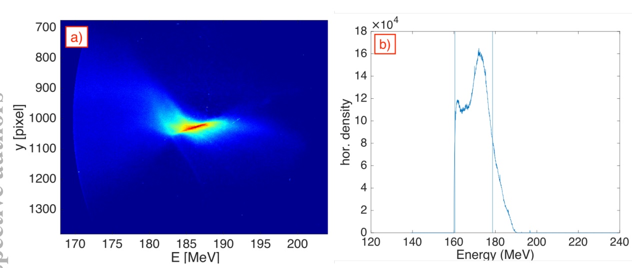

Figure 5: Electron beam energy spectrum: (a) raw image on screen 2, (b) energy profile.

BEAM TRANSPORT

The proper tuning of the QUAPEVAs at the source allowed us to transport the electron beam all along the COXINEL line, down to the beam dump. Experimental observation of the beam for different electron generation processes are presented in Fig. 6 before and after the undulator.

The presence of low energy electrons from the broad band mode, produces halos (Fig. 6a and Fig. 6c) coming from

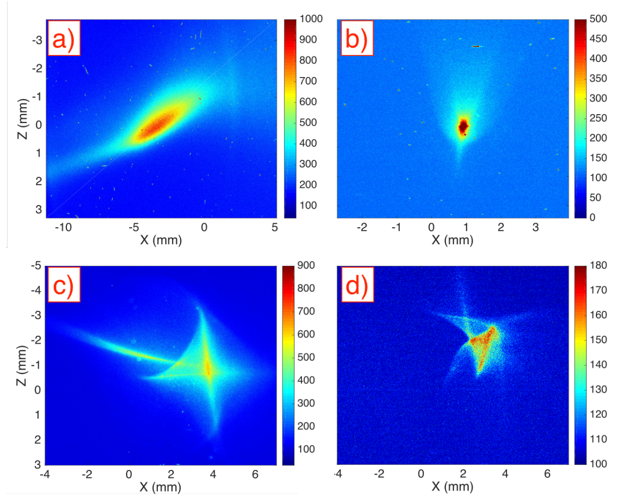

Figure 6: Electron beam at the entrance and exit of the undulator, for different electron generation process: Screen 4, before undulator : (a) Broad Band mode (b) Shock injection mode. Screen 5, after undulator: (a) Broad Band mode, (d) Shock injection mode.

unfocused electrons that have not the correct energy, and increase the observed beam size in comparison to the shock injection mode (Fig. 6b and Fig. 6d).

CONCLUSION

The experimental observations confirm that it is possible to properly transport the electron beam with the desired energy. The electron beam is now controled along the COXINEL line. Spontaneous emission from a U18 undulator has been observed for different electron beam transport setups. The observation of spontaneous emission from the undulator is a first step toward the demonstration of FEL amplification.

ACKNOWLEDGEMENT

The authors are grateful to the support from the European Research Council for COXINEL (340015) and X-Five advanced grants (339128), the French- Swedish collaboration for the support on the U15 cryo-ready undulator, the “Triangle de la Physique” for the QUAPEVA valorisation contract and to J. L. Lancelot, F. Forest and O. Cosson from Sigmaphi for their involvement in the project.

REFERENCES

[1] T. Tajima and J. M. Dawson. Laser electron accelerator. *Phys. Rev. Lett.*, 43:267–270, Jul 1979.

[2] 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.

[3] V. Malka, J. Faure, C. Rechatin, A. Ben-Ismail, J. Lim, X. Davoine, and E. Lefebvre, “Laser-driven accelerators by colliding pulses injection: A review of simulation and experimental results,” *Physics of Plasmas (1994-present)*, vol. 16, no. 5, p. 056703, 2009.

[4] W P. Leemans, A. J. Gonsalves, H.-S. Mao, K. Nakamura, C. Benedetti, C. B. Schroeder, Cs. Toth, J. Daniels, D. E. Mittelberger, S. S. Bulanov, J.-L. Vay, C. G. R. Geddes, and E. Esarey. "Multi-GeV electron beams from capillary-discharge-guided subpetaWatt laser pulses in the self-trapping regime," *Physical Review Letters*, vol. 113, p. 245002, Dec 2014.

[5] M. Couprie, M. Labat, C. Evain, C. Szwaj, S. Bielawski, N. Hubert, C. Benabderrahmane, F. Briquez, L. Chapuis, F. Marteau, *et al.*, "Strategies towards a compact XUV free electron laser adopted for the LUNEX5 project," *Journal of Modern Optics*, pp. 1–13, 2015.

[6] M. Couprie, M. Labat, C. Evain, F. Marteau, F. Briquez, M. Khojoyan, C. Benabderrahmane, L. Chapuis, N. Hubert, C. Bourassin-Bouchet, *et al.*, "An application of laser–plasma acceleration: towards a free-electron laser amplification," *Plasma Physics and Controlled Fusion*, vol. 58, no. 3, p. 034020, 2016.

[7] M.-E. Couprie, C. Benabderrahmane, L. Cassinari, J. Daillant, C. Herbeaux, N. Hubert, M. Labat, A. Loulergue, P. Marchand, O. Marcouillé, *et al.*, "Progress of the LUNEX5 project," in *35th International Free-Electron Laser Conference (FEL 2013)*, pp. 502–506, Joint Accelerator Conferences Website, 2013.

[8] M.-E. Couprie, C. Benabderrahmane, P. Berteaud, S. Bielawski, C. Bourassin-Bouchet, F. Bouvet, *et al.*, "Advances on the LUNEX5 and COXINEL Projects", in *Proc. 37th International Free Electron Laser Conference (FEL2015)*, Daejeon, Republic of Korea, August 2015, paper WEP078, pp. 730–734, ISBN: 978-3-95450-134-2, `http://accelconf.web.cern.ch/AccelConf/FEL2015/papers/wep078.pdf`, doi:10.18429/JACoW-FEL2015-WEP078, 2015.

[9] M. Couprie, C. Benabderrahmane, P. Berteaud, C. Bourassin-Bouchet, F. Bouvet, F. Briquez, L. Cassinari, L. Chapuis, M. El Ajjouri, C. Herbeaux, *et al.*, "Experiment preparation towards a demonstration of laser plasma based free electron laser amplification," *Proc. FEL'14 (Basel, Switzerland*, 2014.

[10] T. Andre, I. Andriyash, C. Basset, C. Benabderrahmane, P. Berteaud, S. Bielawski, S. Bonnin, F. Bouvet, F. Briquez, L. Cassinari, et al. First electron beam measurements on coxinel. In *7th International Particle Accelerator Conference (IPAC'16), Busan, Korea, May 8-13, 2016*, pages 712–715. JACOW, Geneva, Switzerland, 2016.

[11] M. Khojoyan, F. Briquez, M. Labat, A. Loulergue, O. Marcouillé, F. Marteau, G. Sharma, and M. Couprie, "Transport studies of LPA electron beam towards the FEL amplification at COXINEL," *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 2016. `http://dx.doi.org/10.1016/j.nima.2016.02.030`

[12] C. McGuffey, A. Thomas, W. Schumaker, T. Matsuoka, V. Chvykov, F. Dollar, G. Kalintchenko, V. Yanovsky, A. Maksimchuk, K. Krushelnick, *et al.*, "Ionization induced trapping in a laser wakefield accelerator," *Physical Review Letters*, vol. 104, no. 2, p. 025004, 2010.

[13] P. N'gotta, T. Andre, L. Chapuis, M-E. Couprie, A. Ghaith, F. Marteau, M. Valléau, J. Vétéran, C. Benabderrahmane, O. Cosson, F. Forest, "Tunable High Gradient Permanent Magnets Quadrupoles (QUAPEVA)", presented at IPAC'17, Copenhagen, Denmark, May 2015, paper THPIK006, this conference.

[14] M.-E. Couprie, A. Loulergue, M. Labat, R. Lehe, and V. Malka, "Towards a free electron laser based on laser plasma accelerators," *Journal of Physics B: Atomic, Molecular and Optical Physics*, vol. 47, no. 23, p. 234001, 2014.

[15] A. Maier, A. Meseck, S. Reiche, C. Schroeder, T. Seggebrock, and F. Gruener, "Demonstration scheme for a laser-plasma-driven free-electron laser," *Physical Review X*, vol. 2, no. 3, p. 031019, 2012.

[16] T.I. Smith, J.M.J. Madey, L.R. Elias, and D.A.G. Deacon, "Reducing the sensitivity of a free-electron laser to electron energy," *Journal of Applied Physics*, vol. 50, no. 7, pp. 4580–4583, 1979.

[17] C. Benabderrahmane, M. Valléau, A. Ghaith, P. Berteaud, L. Chapuis, F. Marteau, F. Briquez, O. Marcouillé, J.-L. Marlats, K. Tavakoli, A. Mary, D. Zerbib, A. Lestrade, M. Louvet, P. Brunelle, K. Medjoubi, C. Herbeaux, N. Béchu, P. Rommeluere, A. Somogyi, O. Chubar, C. Kitegi, and M.-E. Couprie. 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. Accel. Beams*, 20:033201, Mar 2017.

[18] A. Ghaith, M. Valléau, F. Briquez, G. Sharma, F. Marteau, M. E. Couprie, P. Berteaud, C. Kitegi, M. Tilmont, J. Da Silva Castro, K. Tavakoli, J. M. Dubuisson, D. Zerbib, N. Béchu, C. Herbeaux, M. Sebdaoui, C. Benabderrahmane, O. Marcouillé, A. Lestrade, A. Somogyi, "Progress of PrFeB Based Hybrid Cryogenic Undulators at SOLEIL", presented at IPAC'17, Copenhagen, Denmark, May 2015, paper TUOAA3, this conference.

[19] A. Loulergue, M. Labat, C. Evain, C. Benabderrahmane, V. Malka, and M. Couprie, "Beam manipulation for compact laser wakefield accelerator based free-electron lasers," *New Journal of Physics*, vol. 17, no. 2, p. 023028, 2015.

[20] M Labat, N Hubert, M El Ajjouri, L Cassinari, C Bourrassin-Bouchet, A Loulergue, and ME Couprie. Electron beam diagnostics for coxinel. *Proc. FEL'14*, 2014.

ISBN 978-3-95450-182-3