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STUDY OF THE ELECTRON TRANSPORT IN THE COXINEL FEL BEAMLINE USING A LASER-PLASMA ACCELERATED ELECTRON BEAM*

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Abstract

The ERC Advanced Grant COXINEL aims at demonstrating free electron laser (FEL) at 200 nm, based on a laser-plasma accelerator (LPA). To achieve the FEL amplification a transport line was designed to manipulate the beam properties. The 10-m long COXINEL line comprises a first triplet of permanent-magnet variable-strength quadrupoles (QUAPEVA), which handles the large divergence of LPA electrons, a magnetic chicane, which reduces the slice energy spread, and finally a set of electromagnetic quadrupoles, which provides a chromatic focusing in a 2-m undulator. Electrons were successfully transported through the line from LPA with ionization-assisted self-injection (broad energy spectra up to 250 MeV, few-milliradian divergence).

INTRODUCTION

Today, LPAs [1–3] can deliver over few millimeters of acceleration distances, relativistic electron beams with energies from hundreds MeV to few GeV [4] of few femtosecond durations and high peak currents in the multi-kiloAmps range. While transported and accelerated in the laser wake field, electrons acquire significant spread of the transverse and longitudinal momenta, leading to degradation of beam quality ($\sigma_{x'} \approx 1$ mrad and $\sigma_\delta \approx 1\%$ [5]). So far LPA-based undulator radiation has been observed [6–10] but application of such beams for FEL remains very challenging. The large divergence can be handled by means of high gradient quarupoles or plasma lens [11, 12], while the energy spread can be reduced using a demixing magnetic chicane [13, 14] or being compensated in a Transverse Gradient Undulator [15, 16]. Among other LPA-based FEL projects [13,17,18], COXINEL [19–22] is part of the French FEL project LUNEX5 [23–25]. A transport line was designed to handle the large divergence of LPA electrons thanks to strong permanent magnet quadrupoles, a magnetic chicane permits to reduce the slice energy spread and a chromatic focusing in the undulator was developed to improve FEL performance [26].

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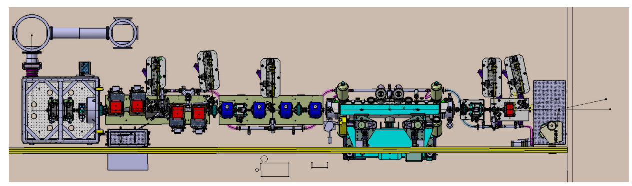

Figure 1: General top view of the COXINEL LPA demonstration set-up. From left to right: LPA chamber (gray) with the first set of quadrupoles, magnetic chicane dipoles (red), quadruplet of quadrupoles (blue), undulator (2-m U18 shown), dipole for beam dump (red), and UV-spectrometer (brown).

TRANSPORT LINE DESCRIPTION

The transport line was designed, build and characterized at SOLEIL, then installed and aligned with the laser line of the "Salle Jaune" laser system of Laboratoire d'Optique Appliquée (see Fig. 1).

The laser plasma acceleration is performed with a Ti:Sa laser system that delivers 800 nm, 30 fs (FWHM), 30 PW pulses. A first triplet of quadrupoles, called QUAPEVA [27], is immediately installed after the source. These quadrupoles are built with permanent magnets, but have an original design for gradient variation and magnetic center adjustment for flexible refocusing [28, 29]. The beam is then manipulated in a magnetic chicane composed of four electromagnetic dipoles followed by a set of four electromagnetic quadrupoles (QEM) to provide electron beam focusing inside a cryo-ready U18 undulator [30, 31]. Electron diagnostics such as turbo-Integrated Current Transformer, cavity Beam Position Monitors, and multiple scintillating screens, are installed every 1–2 m along the beam line [32]. Two photons diagnostic devices, an under vacuum CCD camera and a photon spectrometer, are installed at the exit of the undulator.

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Table 1: Properties of the Magnetic Equipment for Modeling the Beam Line for Central Energy of $E = 176$ MeV

Equipment	Properties	Values	
		Chromatic Matching	Strong Focusing
QUAPEVAs	Gradient (QUAPEVA1)	102.8 [T/m]	101.9 [T/m]
	Gradient (QUAPEVA2)	-101.2 [T/m]	-99.97 [T/m]
	Gradient (QUAPEVA3)	88.17 [T/m]	88.82 [T/m]
Dipoles	r_{56}	4.3 [mm]	
	$B\rho$ @176 MeV	0.60 [T.m]	
Quadrupoles	Gradient (QEM 1)	-2.43 [T/m]	0 [T/m]
	Gradient (QEM 2)	3.98 [T/m]	0 [T/m]
	Gradient (QEM 3)	-5.76 [T/m]	0 [T/m]
	Gradient (QEM 4)	2.14 [T/m]	0 [T/m]
Undulator	Period	18 [mm]	
	Peak Field (5-mm gap)	1.156 [T]	
	Magnetic Length	2	
	K (5-mm gap)	1.94	

MODELING OF THE LINE

Here, numerical simulations, using a hand-made Matlab code [33, 34], are done for a more realistic case than the reference one [19]. A deteriorated LPA beam with an energy spread of 5%, a divergence of $\sigma'_x = \sigma'_z = 3$ mrad and an emittance: $\epsilon = 1$ mm.mrad, for a reference energy of 176 MeV is considered. Table 1 summarizes the characteristics of the magnetic equipment composing the beam line.

Energy spread has a significant impact on the FEL amplification and should be lower than the Pierce parameter ($\sigma_\delta \ll \rho_{\mathrm{FEL}}$) [35]. A strategy to reduce the large energy spread of LPA beam ($\approx 1\%$) is to stretch it longitudinally in a chicane where a correlation between the longitudinal position and energy is created. The stretching factor is defined by:

$$C = \frac{1}{1 + h \cdot R_{56}} \quad \text{and} \quad h = \frac{\Delta E}{E_0} \cdot \frac{1}{l_b},$$

where R_{56} is the strength of the chicane, ΔE is the uncorrelated energy spread of the beam, E_0 is the nominal energy and l_b is bunch length at the entrance of the chicane. The length of the stretched bunch is given by:

$$\sigma_s = \frac{l_b}{C}, \tag{1}$$

Figure 2 shows the phase-space of the beam before and after the chicane for a strong R_{56} value. In the simulation shown in Fig. 2, $E = 176$ MeV, $\sigma'_x = \sigma'_z = 3$ mrad, $\sigma_\delta = 5\%$, $N_p = 10^6$, $q = 34$ pC, and $R_{56} = 4.3$ mm. Machine parameters match the values listed in Table 1. The longitudinal beam size input is 5 µm. With an energy spread of 5%, the stretching factor is $C = 0.0227$, leading to a beam size at the exit of the chicane of 220.3 µm, which is in a good agreement with the numerical result of 220.5 µm. In this configuration the energy spread is well reduced.

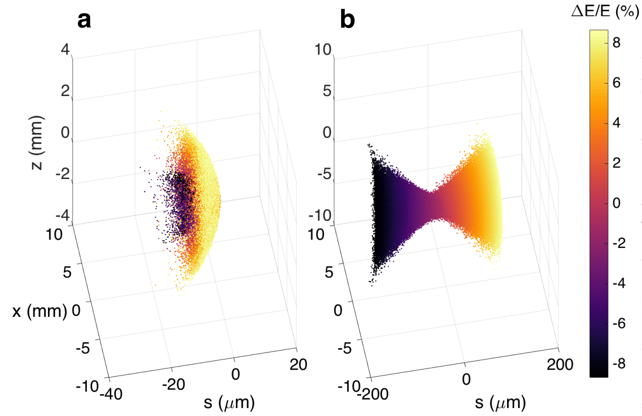

Figure 2: Simualted beam phase space (a) before chicane and (b) after chicane.

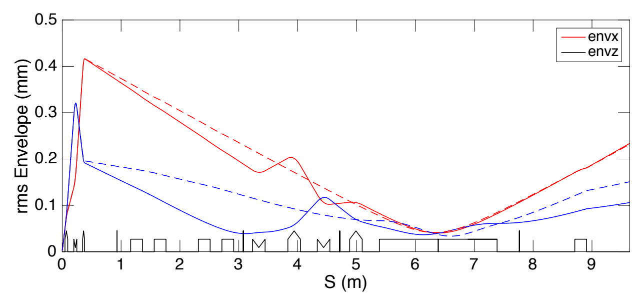

Figure 3: Beam envelopes for a 176-MeV reference energy, using different optics in COXINEL: strong focusing (dashed lines) or chromatic focusing (solid lines).

The lengthening of the beam size process can also be combined with a chromatic focusing (CF) to enhance the FEL amplification process [26]. In this configuration, the set of four quadrupoles before the undulator, is used to focus each slice of the beam at a specific location inside the undulator.

Figure 3 compares the beam dynamics using this chromatic focusing to one without using electromagnetic quadrupoles, known as Strong Focusing (SF). Due to the large divergence of the electron beam, the transverse beam sizes increase dramatically in the first centimeters. Thanks to the strong quadrupoles, the beam can be controlled all along the line.

Figure 4 shows a comparison of the transverse phase-space in the middle of the undulator for these two focusing settings. This comparison uses the same beam and machine parameters as before: $E = 176$ MeV, $\sigma'_x = \sigma'_z = 3$ mrad, $\sigma_\delta = 5\%$, $N_p = 10^6$, $q = 34$ pC, $R_{56} = 4.3$ mm, and the machine parameters listed in Table 1. The tilt of the beam in phase-space shown in Fig. 4 (a) and (b) informs about the slice focusing. In this case only the central energy is well focused in the middle of the undulator compared to CF optics where all the slices are focused in a specific location.

For low energy spread and low divergence, the transmission of the beam line is 100%, but when considering more realistic beam parameters the transmission of the beam line is reduced (see Fig. 5). In both CF and SF cases, losses start

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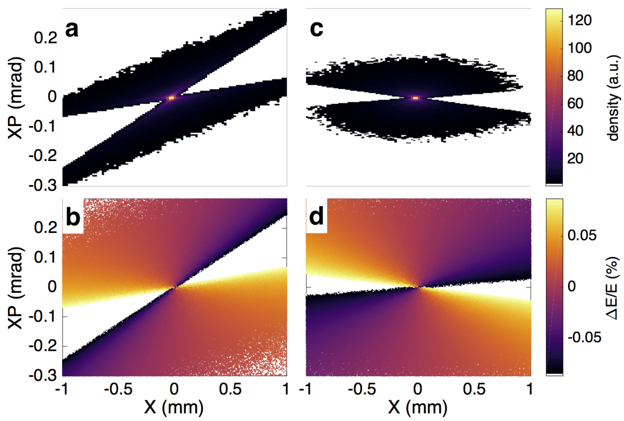

Figure 4: Beam phase-space in the middle of the undulator: The left plots present the xx' phase space in (a) density and (b) energy representation using SF optics; the right plots present the xx' phase space in (c) density and (d) energy representation using CF optics.

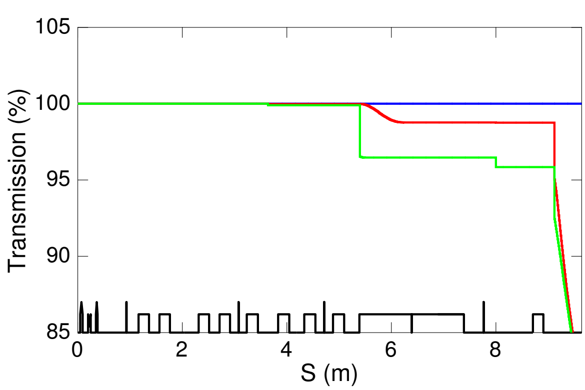

Figure 5: Transmission of the beam line using different optics: Chromatic focusing with $\sigma'_x = \sigma'_z = 1$ mrad, $\sigma_\delta = 1\%$ (blue). Chromatic focusing with $\sigma'_x = \sigma'_z = 3$ mrad, $\sigma_\delta = 5\%$ (red). Strong focusing with $\sigma'_x = \sigma'_z = 3$ mrad, $\sigma_\delta = 5\%$ (green).

to appear after the chicane but in the SF case, the losses are greater due to the optics properties.

TRANSPORT RESULTS

For reliability of electron production, the first experiments were done using self-injection and ionization injection mechanisms [36] where the laser is focused on a spot of 10–15 µm size in a supersonic jet of a gas mixture composed of 99% helium and 1% nitrogen. This method of production creates an electron beam with high divergence and a wide energy spectrum (50–250 MeV). In this configuration, the beam properties are far from the reference case, but a proper tuning of the equipment allowed us to transport the electron beam all along the COXINEL line, down to the beam dump and control its properties.

CONCLUSION

The experimental observations confirm that it is possible to properly transport the electron beam and control its properties. Comparison of the simulations and experiments are in good agreement. Despite the significant difference of the electron beam parameters in the realistic and reference cases, the handle of the transport open the way to the observation of spontaneous emission of the undulator, a first step towards FEL amplification.

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