An application of laser–plasma acceleration: towards a free-electron laser amplification

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Abstract

The laser–plasma accelerator (LPA) presently provides electron beams with a typical current of a few kA, a bunch length of a few fs, energy in the few hundred MeV to several GeV range, a divergence of typically 1 mrad, an energy spread of the order of 1%, and a normalized emittance of the order of $\pi \cdot \text{mm.mrad}$. One of the first applications could be to use these beams for the production of radiation: undulator emission has been observed but the rather large energy spread (1%) and divergence (1 mrad) prevent straightforward free-electron laser (FEL) amplification. An adequate beam manipulation through the transport to the undulator is then required. The key concept proposed here relies on an innovative electron beam longitudinal and transverse manipulation in the transport towards an undulator: a ‘demixing’ chicane sorts the electrons according to their energy and reduces the spread from 1% to one slice of a few ‰ and the effective transverse size is maintained constant along the undulator (supermatching) by a proper synchronization of the electron beam focusing with the progress of the optical wave. A test experiment for the demonstration of FEL amplification with an LPA is under preparation. Electron beam transport follows different steps with strong focusing with permanent magnet quadrupoles of variable strength, a demixing chicane with conventional dipoles, and a second set of quadrupoles for further focusing in the undulator. The FEL simulations and the progress of the preparation of the experiment are presented.
Keywords: free-electron laser, laser–plasma accelerator, undulator

Introduction

Accelerator-based light sources are widely developed nowadays [1, 2]. The use of synchrotron radiation first started parasitically on high-energy physics accelerators to dedicated storage rings, and then moved onto the second generation with a few insertion devices, and onto the third generation with a high number of undulators and wigglers, with a low value of emittance, enabling partial transverse coherence, with the prospect of diffraction-limited storage rings [3]. Relativistic electrons passing through an undulator creating a periodic permanent field (period $\lambda_u$ and peak magnetic field $B_u$ in the planar case) [5] wiggle and emit radiation on a series of harmonics with the so-called resonance condition for the n-th of order harmonics $\lambda = \lambda_u(1 + K_n^2/2n^2)$, with the deflection parameter $K_n = 0.94\lambda_d/cmB_u(T)$, and $T$ the normalized electron beam energy to its rest energy. Radiation from the different periods positively interferes. Longitudinal coherence and short pulses are provided with the free-electron laser (FEL) process [6], on the so-called fourth generation light sources, leading to an increase in the peak brilliance by several orders of magnitude with respect to synchrotron radiation-based light sources. In an FEL, electrons in the undulator provide the gain medium: a light wave of wavelength $\lambda$ (undulator synchrotron radiation, external seed tuned to the undulator resonant wavelength) interacts with the electron bunch, inducing an energy modulation of the electrons, which is gradually transformed into density modulation at $\lambda$, enabling phased electrons to coherently emit emission at $\lambda$ and its harmonics, enabling partial transverse coherence, with the prospect of diffraction-limited storage rings [3].

1. Strategies for LWFA beam handling for FEL application

In a laser–plasma wakefield accelerator [78–80], an intense laser pulse is focused in a light gas or in a mixture of heavy and light gases [81]. The rising edge of the laser ionizes the gas and creates a plasma. As the laser pulse propagates in the plasma, the ponderomotive force expels electrons from the optical axis, thus forming a cavity free of electrons in the laser wake. The fields in this cavity have very large amplitudes, up to hundreds of giga-electronvolts by meters. As a result, electrons trapped in the cavity can be accelerated to giga-electron-volt energies in just a few millimeters.

For now, the stable and controlled injection of electrons into the accelerating plasma cavities remains an important challenge, and considerable effort has been made for many years to establish such a control, and thus to improve the quality of the resulting beams. For this, a wide range of injection techniques was considered theoretically and experimentally, e.g. injection-colliding laser pulses [82], density transition injection [83], near-threshold injection [84], ionization injection [85], etc. Typical electron beams have energies of a few hundred MeV (up to 4 GeV [86, 87]), charges of a few tens of pico-coulomb, femtosecond durations [88], relative energy spreads of a few percent (1% at best [89]) and emittances below 1 $\mu$m [90]. Electron beam performance [91–95] depends on the
adopted configuration, and typically one can consider getting a few hundred MeV electron beam of tens of pC charge, with 1 μm transverse size, 1 mrad divergence with 1 μm longitudinal size (normalized emittance of 1 π.mm.mrad), few femtosecond duration and 1% energy spread, i.e. two orders of magnitude larger energy spread and three orders of magnitude larger divergence than electrons issued from a conventional linear accelerator, while the electron bunch is generally rather short. Without appropriate electron beam transport, the electron bunch length and emittance cannot be preserved, because of the large electron beam divergence [96–98]. The beam divergence requires a strong focusing with adapted quadrupoles of high gradient close to the electron source and/or with a plasma lens [97]. So far, only LWFA-based undulator spontaneous emission has been observed [99–103].

However, in view of an FEL application [104–108], the large energy spread value is also an issue. Two strategies of longitudinal beam manipulation are considered. The first consists of passing the electron beam through a decompression chicane, which sorts the electrons according to their energy and can typically reduce the slice energy spread, a critical feature for the FEL application, by one order of magnitude [109–111]. Moreover, taking advantage of the introduced correlation between the energy and the position, the slices can be focused in synchronization with the optical wave advance, in the so-called chromatic matching scheme [112], resulting in an additional spatial manipulation. Test experiments are under preparation at Berkeley [113, 114], CFEL [115], and SOLEIL in collaboration with Laboratoire d’Optique Appliquée and Univ. Lille [116–118]. The second concept for handling the large energy spread of LWFA consists of using a transverse gradient undulator [119–121] creating an additional transverse focus thanks to canted magnetic poles in addition to the longitudinal periodic magnetic field. A linear transverse dependence of the vertical undulator field is thus generated, according to $K(x) = K_0(1 + \alpha x)$ with $\alpha$ the gradient coefficient. Associated to optics with dispersion introducing a transverse displacement $x$ with the energy according to $x = \eta \Delta \gamma / \gamma$, the resonant condition is fulfilled for $\eta = (2 + K_0^2) / \alpha K_0^2$ even though the initial energy spread is larger. Consequences for the FEL features have been further investigated [122–124]. An experimental implementation of such a scheme is under progress at F. Shiller Univ., Jena, in collaboration with KIT [125, 126] with a superconducting transverse gradient undulator (TGU) [127–130].

2. Towards LWFA FEL amplification: beam manipulation on COXINEL

First, assuming that the electron beam is directly transported and focused in the undulator in the case of LUNEX5, one can examine what could be done in terms of the FEL with the LPA. Figure 2 illustrates GENESIS [131] calculations performed...
at 19.5 nm for different values of the energy spread 0.1, 0.5 and 1%. Figure 2(a) shows the FEL amplification while the electron bunch is progressing inside the undulator segments (between the segments, amplification is stopped and the signal remains constant). Only in the case of 0.1% energy spread, does the FEL power reach the usual GW peak power level. Figure 2(b) exhibits the longitudinal distribution of the radiation. The shape of the pulse is deformed in the 0.5 and 1% energy spread case, the longitudinal coherence is not properly built and the FEL is not yet properly established. Figure 2(c) shows the spectral profile of the radiation in the three cases of energy spread: it is extremely noisy in the 1% energy spread case and does not have the expected laser properties. Only the case of an energy spread of 0.1% exhibits nice spectral and temporal profiles. It is also highly optimistic since the electron beam parameters have been directly introduced in the FEL simulations without taking into account the electron beam degradation that might occur during its transport to the undulator. Another more secure solution has thus to be implemented.

In order to have a more reasonable approach, a dedicated transfer line enabling manipulation of the electron beam properties has been designed, as shown in figure 3. The experiment is first set for a 200 nm operation with a 180 MeV electron beam, before going at a shorter wavelength (aiming at 40 nm) with a 400 MeV electron beam. The optimization at 180 MeV is described here.

The intense laser is focused down to a gas cell for the electron production. The electron beam transport line is composed of a first triplet of quadrupoles located just after the gas cell, a chicane of four dipoles for the decompression (see figure 3) and a seeding port. Figure 3 shows the effect of the chicane on the longitudinal properties. Longitudinal phase space before (left) and after (right) the chicane. $dE/E$: relative energy difference, $Z$: longitudinal position.

Figure 3. Sketch of the proposed beam transfer line from the laser hutch and electron beam generation in the gas cell, including the seed and down to the FEL diagnostic station.

Figure 4. Effect of the chicane on the electron beam longitudinal properties. Longitudinal phase space before (left) and after (right) the chicane. $dE/E$: relative energy difference, $Z$: longitudinal position.

Figure 5. Schematic of the chromatic matching: left transverse phase (X: horizontal position, XP: horizontal angle): right: transverse size along the longitudinal position along the undulator.
Then, the transport line accommodates a second set of quadrupoles for performing the adequate focusing for proper interaction between the electrons and photons, the undulator, an electron beam dump, and a monochromator. The chromatic matching can be applied, as shown in figure 5. Four correctors are also set along the transport, two surrounding the chicane and two the undulator.

Electron linear optics have been designed [132] to image the source in the undulator, with a magnification of 20, and to synchronize the electron bunch slice focus, together with the optical wave propagation according to the chromatic matching concept [112] using BETA [133] code associated to a 6D symplectic tracking and ASTRA [134]. A Gaussian distribution has been considered for the transport and FEL optimization, intending first to cope with the large values of the energy spread and divergence. These types of distributions provide a first basis for the understanding and optimization of the electron beam dynamics. In reality, LPA beams have a more complicated phase structure, such as energy chirp [135] but the concept of chromatic matching should also be suitable in principle to handle the chirp in the LPA electron beams. Indeed, a linear chirp would only induce a small shift in the chicane strength, which is a scanned parameter.

The optical functions are shown in figure 6. The maximum electron beam deviation in the chicane is 32 mm.

The nonlinear study considers, in addition, the contribution of the chromatic emittance, and the additional sources of bunch lengthening. The natural undulator focusing is also taken into account. Collective effects such as space charge and coherent synchrotron radiation have also been considered. They lead to a slight increase in the emittance, with respect to the case neglecting these collective effects. Impedance and resistive wall have still to be included. They lead to a slight increase in the emittance, with respect to the case neglecting these collective effects. Impedance and resistive wall have still to be included. The main obtained COXINEL parameters for the 180 MeV case are listed in table 1. The dipole enable an 80 mrad deviation and give a maximum bunch decompression strength $r_{56} = 4.3 \text{ mm}$ at 400 MeV.

Two different undulators will be used. Their characteristics are given in table 2. The seeded FEL power calculated with the baseline parameters for the 200 and 40 nm cases versus the chicane strength is plotted in figure 7. The optimum is rather smooth and differs in the two operating points. The FEL power is amplified by several orders of magnitude and it reaches the 10 MW range. The FEL pulse duration is typically 15 fs FWHM. The FEL performance is, however, highly dependent on the electron beam characteristics. Getting the FEL amplification is still very challenging.

### 3. Towards LWFA FEL amplification: experiment preparation on COXINEL

#### 3.1. General integration

Even though the acceleration process in plasma is very compact, the necessary electron beam manipulation requires some magnetic elements, diagnostics and the overall implementation is not straightforward. In the COXINEL planned experiment, the transfer line equipment is designed, built and measured at SOLEIL before being implemented in the Salle Jaune of Laboratoire d’Optique Appliquée, where the electrons are generated. The general integration had to fit in 11 m from the electron source to the end of the FEL characterization equipment (see figure 8). In order to accommodate the different components in the available space, steerters, one cavity beam position monitor and diagnostics have been set just after the permanent magnet quadrupoles. The first triplet of quadrupoles, one current

![Figure 6. Optical functions along the COXINEL line at 180 MeV.](image-url)

![Table 1. Main COXINEL electron parameters at 180 MeV.](table-url)
transformer and the first steerer will also be put directly into the chamber containing the gas cell. The vacuum level will be about $10^{-4}$ mbar in the gas jet area. In the transfer line, three turbo-molecular pumps, connected by soft bellows for limiting the vibration level are implemented all along the line, enabling them to reach a $10^{-6}$ mbar level. The usual ionic pumps of the undulator are changed to turbo-molecular ones.

### 3.2. Laser-plasma acceleration of electrons

Electrons will be generated with the Salle Jaune laser facility at LOA which delivers two 60 TW laser pulses at a central wavelength of 810 nm. The energy in each beam is about 1.6 J and the laser duration is 28 fs. One of the beams will be focused in a supersonic helium gas jet or in a gas mixture, with an f/15 off-axis parabola mirror. A controlled injection technique, such as colliding injection [82] or density transition injection [85] will be used to produce a stable electron beam with energy of 180 MeV, a divergence below 2 mrad and a relative energy spread below 3%. A laser-plasma lens [99] could be used to reduce the beam divergence below 1 mrad.

A leak of the main Ti–Sa laser driving the electron generation will also be used to generate high-order harmonics in gas, to be used as a seed. The seeding light will be injected via a viewport using a mirror located in the middle of the chicane. Different mirror systems will be chosen for the different spectral ranges.

### 3.3. Magnetic elements and power supplies of the transport line

The characteristics of the COXINEL magnetic elements are listed in table 3. The magnetic elements have been designed and optimized with respect to the electron beam dynamics using RADIA [136] and TOSCA [137] magnetic software.

The first triplet is made of permanent magnet quadrupoles (so-called QUAPEVA) enabling it to achieve the required strength for the given bore diameter. A specific design has been carried out in TOSCA to enable sufficient strength variation. It is under preparation in collaboration with Sigmaphi.

The chicane is composed of four identical water-cooled electromagnetic dipoles. Manufactured by SEF, they have been measured at SOLEIL with a rotating coil and a Hall probe. The measured field integrals, as shown in figure 9(a), are in agreement with the expected calculations from the RADIA and TOSCA models. A magnetic-field mapping is presented in figure 9(b). A good agreement is obtained between

| Component                        | Characteristics  | Unit | Value |
|----------------------------------|------------------|------|-------|
| First triplet of quadrupoles     | Gradient         | T m$^{-1}$ | 102/103/91 |
|                                  | (180 MeV)        |      |       |
|                                  | Gradient         | T m$^{-1}$ | 142.2/142.3/133.4 |
|                                  | (400 MeV)        |      |       |
|                                  | Bore diameter    | mm   | 12    |
| Chicane                          | Dipole field     | T    | 0.565 |
|                                  | Gap              | mm   | 25    |
|                                  | Maximum deviation| mm T m | 132   |
| Dipole power supply              | Current          | A    | 150   |
|                                  | Voltage          | V    | 8     |
|                                  | Accuracy         | ppm  | 15    |
| Second set of quadrupoles        | Gradient         | T m$^{-1}$ | 20    |
|                                  | Bore diameter    | mm   | 25    |
|                                  | Length           | mm   | 200   |
| Steerers                         | Field            | T    | 0.35  |
| Steerer/quadrupole power supplies| Current          | A    | 10    |
|                                  | Voltage          | V    | 10    |
|                                  | Accuracy         | ppm  | 20    |
| Beam dump dipole                 | Field            | T    | 1     |

For the 200 nm case and for the 40 nm case versus the chicane strength. Parameters of tables 1 and 2, seed of 10 kW.

Figure 7. FEL power for the 200 nm case and for the 40 nm case versus the chicane strength. Parameters of tables 1 and 2, seed of 10 kW.

**Table 2. COXINEL undulator characteristics.**

| Characteristics | Unit    | U20 | U15 |
|-----------------|---------|-----|-----|
| Period          | mm      | 20  | 15  |
| Number of periods|         | 98  | 200 |
| Minimum gap     | mm      | 5.5 | 3   |
| Peak field (293 K) | T   | 1   | 1.53 |
| Peak field (77 K)  | T    |     | 1.65 |
| Technology      | In-vacuum, hybrid |   |     |
| Permanent magnets| NdFeB | PrFeB |
| Poles           | Vanadium Permendur |     | Vanadium Permendur |

**Table 3. Magnetic elements of the COXINEL transport line.**
simulations and measurements. Four independent bipolar power supplies feed the dipoles. The power supplies (manufactured by Sigmaphi Electronics) are tested at SOLEIL.

The quadrupoles of the second set are electromagnetic air-cooled components. They are manufactured by SEF. The steerers are air-cooled electromagnetic devices, also manufactured by SEF.

The steerer and quadrupole power supplies (±10 A, 10V, 16 bit resolution) are bipolar. They are manufactured by Sigmaphi Electronics.

The beam dump dipole is constituted of permanent magnets.

3.4. Diagnostics

3.4.1. Electron diagnostics. The interceptive position and transverse measurements of the electrons by imaging the electron beam hitting one screen inserted at 45°, are established thanks to the diagnostic stations [138]. These stations include a translation stage with an OTR screen, a YAG:Ce or LYSO:Ce screen and calibration grid, associated with a re-imaging achromatic system on a CCD camera (Basler series scA640-70gm) with two magnifications enabling one to adjust the resolution depending on the purpose. A set of neutral densities is mounted on a motorized filter wheel to adapt the incident intensity on the CCD. Since coherent optical transition radiation can become an issue, appropriate simulations are in progress. There are six of them, installed at different locations (just after the first triplet, in the chicane, on the first beam dump, at the entrance and exit of the undulator, and on the final beam dump).

Non-interceptive beam position measurements will be done with two cavity beam position monitors (cavity BPM) from the Paul Sherrer Institute [139], to be installed at the entrance and exit of the undulator. The expected resolution is below 1 μm even at low charge. In addition, a stripline, under design at SOLEIL, will provide a resolution of 30 μm at 1 pC. It will be easier to operate. It will be installed at the exit of the undulator.

The electron beam energy and energy spread can be measured using a standard imager after a dipole magnet in a dispersive section of the transport beam line.
The electron beam charge will be measured just after the first triplet and at the undulator exit, using a commercial integrated current transformer (ICT) (Bergoz) adapted from a low charge (10 pC).

The ICT and the cavity BPM are under test on the Synchrotron SOLEIL transfer line. So far, expected performances are currently being achieved.

3.4.2. Photon diagnostics. The spectral measurement (spontaneous emission, seed, FEL) will be done using a spectrometer located 3 m downstream from the undulator exit. First, for the UV-visible spectral range, an iHR320 spectrometer (Horiba), equipped with a Synapse back-illuminated CCD and a plane holographic grating, will enable single-shot measurement of the radiation spectrum. For a shorter wavelength, the use of a customized version of a PGM200 spectrometer (Horiba) is foreseen and under investigation. By coupling a toroidal mirror and a set of planar gratings, this device will enable the measurement of spectra from 200 down to 10 nm.

3.5. Undulators
The first 2 m long in-vacuum hybrid undulator is already built. The magnetic field measurement is shown in figure 10. Then, a 3 m long U15 cryo-ready undulator will be employed. Following the cryogenic undulator built with Pr$_2$Fe$_{14}$B magnets first developed at SOLEIL [140, 141], a typical LUNEX5 U15 module is developed by a French–Swedish collaboration. The use of a Pr$_2$Fe$_{14}$B specific grade with poles in VanadiumPermendur enables operation both at room temperature and at 77 K. The module scheme has been modified for using half-poles, enabling an easier swapping [142, 143].

4. Conclusion and prospects
Recently, tremendous progress has been achieved on electron beam accelerated by laser–plasma interaction. Even though these beams cannot compete yet with electron beam produced by conventional accelerators in terms of energy spread and divergence, it is worth discussing their applications. As an intermediate, before considering future linear colliders based on LPA, it appears that an FEL application could qualify LPA beams, even though achieving an FEL amplification with electrons produced by laser–plasma acceleration is very challenging. Considering electron beam parameters at the limit of what has been measured so far, the simulations presented here show that amplification is possible, providing an adapted transfer line for the manipulation of the electron beam properties in view of the FEL. This manipulation enables one to handle both the electron beam divergence with a first strong focusing, and then to cope with the large energy spread in sorting out the electrons, thus reducing the slice energy spread. In addition, the concept of chromatic matching presented here enables one to turn into advantage the energy to transverse phase-space correlation inside the bunch, for an adapted focusing inside the undulator. Prior to experimental tests to be performed according to the COXINEL studies, such a design requires the optimization and preparation of a significant amount of hardware for the transfer line to the undulator, necessary for enabling the FEL amplification. Issues related to the electron beam stability and repeatability will be even more of a challenge to get the amplification signal.

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Figure 10. Magnetic measurement of the U20 undulator to be used for the COXINEL.
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